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IMPROVE THE SUSTAINABILITY OF SUPPLY CHAIN: THE ROLE OF CARBON ABATEMENT AND BLOCKCHAIN TECHNOLOGY

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Abstract. This paper analytically explores a supply chain where a manufacturer sells products through a retail platform that can operate under either a reselling or agency selling model, corresponding to Scenarios R and A. The model incorporates consumer valuation discounts based on the platform's retail channel and sensitivity to carbon emissions. The paper first examines the manufacturer's investment decision in green technology to reduce carbon emissions and then analyzes the platform's adoption of blockchain technology to disclose information about the manufacturer's actions. The analysis shows that the manufacturer consistently prefers to invest in green technology over taking no action in both scenarios. However, the platform's decision to adopt blockchain depends on consumer acceptance of the product: blockchain is deployed when consumer acceptance is high, and not when it is low. The study further identifies two key factors – consumer acceptance and environmental sensitivity – that critically influence the supply chain members' choice of operational model. Specifically, as consumer acceptance of the product increases, both the manufacturer's and platform's preferences shift from Mode RN/RT (Reselling, No blockchain/Retail, No blockchain) to Mode RB (Reselling, Blockchain) and Mode RT (Agency, Blockchain) to Mode AB (Agency, Blockchain). Conversely, as consumer environmental sensitivity increases, preferences shift in the opposite direction, from Mode RB (Reselling, Blockchain) and Mode AB (Agency, Blockchain) to Mode RN/RT (Reselling, No blockchain) and Mode AN/AT (Agency, No blockchain). These findings highlight the interconnectedness of consumer attitudes toward sustainability and the operational decisions of supply chain members.

Mathematics Subject Classification. C300, C600.

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1. Introduction

Over the past four decades, the frequency and intensity of extreme weather events and natural disasters have significantly increased due to global climate change, posing increasingly severe challenges to human survival and development [17, 49]. Addressing global climate change and reducing emissions to foster low-carbon economies have become a consensus within the international community. The initiative of corporations is transitioning from a focus solely on maximizing profitability to adopting a novel growth approach that recognizes the importance

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of societal and environmental well-being. With organizations embracing a dual mission of profitability and sustainability, the efforts to mitigate climate change are prioritized. According to the 2021 Global Institutional Investor Survey published by MSCI[1], in response to the pandemic, 90% of investors from large institutions with assets exceeding $200 billion indicated their intention to increase investments in ESG (*i.e.*, environment, social, governance). It is more and more significant that, sustainability has already become an intrinsic component of business decision-making. Both consumers and corporate buyers are progressively taking carbon footprints into consideration when making purchasing and investment choices. Consequently, companies have substantial market prospects to distinguish themselves by offering products or services characterized by low- or zero-carbon footprints. According to a report released by NYU Stern School of Business in 2021[2], products marketed with sustainability as a selling point contributed to over half (54.7%) of the growth in the packaged consumer goods market from 2015 to 2019. The growth rate of these sustainability-focused products exceeded that of non-sustainable products by more than seven times. In China, Business Value Magazine and Interface News have released the "China Sustainable Consumption Report" for six consecutive years[3]. The report reveals a rapid increase in Chinese consumers' concern regarding corporate social responsibility, rising from 21% in 2017 to 52% in 2019. Additionally, the influence of price factors on consumers' sustainable consumption behaviors has significantly diminished.

Promoting green development through technological innovation is an inevitable choice to achieve carbon neutrality goals. To accomplish energy conservation and emission reduction targets and foster the development of a low-carbon economy, it is crucial to vigorously advance energy technologies and engage in innovative green and low-carbon technology [11, 32, 47, 51]. Green and low-carbon technology innovation is beneficial for enhancing resource efficiency and reducing resource consumption [25, 29]. It serves as a key approach for addressing climate issues, advancing low-carbon urban development, and establishing a low-carbon economy and sustainable development model [48]. It also represents an effective pathway for China's transition from a high-carbon economy characterized by high energy consumption, high emissions, and high pollution to a low-carbon economy characterized by low energy consumption, low emissions, and low pollution [56]. Google not only adopts green technologies in the energy sector but also employs innovative approaches in the design and operation of its data centers to reduce carbon emissions. They utilize advanced cooling systems and intelligent energy management technologies to maximize the energy efficiency of their data centers. Furthermore, Google is engaged in sustainable city projects, applying intelligent technologies to enhance urban energy utilization efficiency and environmental sustainability.

Given that the traceability of product carbon emissions information significantly influences consumer trust and company performance, some companies are actively enhancing the transparency of their products. Blockchain technology provides a new and effective solution for information disclosure for companies due to its several technical characteristics such as immutability, transparency, traceability, and security [4]. Furthermore, recent commercial applications of blockchain technology have demonstrated that businesses can benefit from product information disclosure using blockchain technology, as it addresses critical trust issues related to product-related information [12, 13, 27, 40]. Supported by blockchain technology, information disclosure on retail platforms plays a more crucial role in consumer purchase behavior [24]. Therefore, how to leverage blockchain technology to solve the problem of product information disclosure is an important topic in both academia and industry during the blockchain era [4, 26, 52]. Retail platforms have the capability to leverage their advantages by adopting blockchain technology to disclose product carbon emissions information to consumers and implement incentivizing measures to promote green consumer behavior. Such measures not only respond to consumers' expectations for sustainable products and enhance consumer loyalty but also, through the transmission effect of e-commerce platforms, impact the supply side and encourage upstream manufacturers to take more proactive actions, reducing carbon emissions and engaging in sustainable production activities. In fact, research has

[1] https://www.msci.com/documents/1296102/22910163/MSCI-Investment-Insights-2021-Report.pdf.

[2] https://www.stern.nyu.edu/experience-stern/about/departments-centers-initiatives/centers-of-research/center-sustainable-business/research/csb -sustainable-market-share-index.

[3] https://corporate.zalando.com/en/technology/leading-way-sustainable-fashion.

already demonstrated that if e-commerce platforms implement more proactive consumer communication and incentives, consumers' green choice behavior can be changed and enhanced. For example, the Zalando Group added a dedicated section for sustainable products on its website and prominently displayed stars next to sustainably certified products. This single measure effectively increased the proportion of consumers choosing (at least one) sustainable product from 18% in early 2020 to 50% by the end of the year[4].

The observed real world industrial practice, including deploying blockchain technology to disclose information and the abatement of carbon emission, motivates this research. On one hand, the manufacturer has an incentive to invest in green technology, so as to reduce carbon emission. On the other hand, the platform inclines to deploy blockchain technology to disclosure the manufacturer's environmental action to consumers. Therefore, it is necessary to deeply explore and understand the interaction between platform blockchain adoption and manufacturer green investment strategies. What's more, in the supply chain, the manufacturer and platform usually cooperate in two modes, *i.e.*, reselling format and agency selling format. The selling format usually affects supply chain members' strategic decisions. Based on the above analyses, this work focuses on the following key issues:

- Whether the manufacturer has an incentive to invest in green technology to reduce carbon emission?
- When the manufacturer invests in carbon abatement, whether the platform has an incentive to deploy blockchain technology to disclose related information to consumers?
- How does the consumer's acceptance of products, preference for the product's traceability information and environmental sensitivity parameters influence the manufacturer's and the platform's optimal decisions?
- How does the selling formats affect the manufacturer's and platform's strategic decisions, that is, the green invest and blockchain adoption decisions?

To solve the above research questions, this paper consider a supply chain including a platform and a manufacturer cooperating in reselling or agency selling format. We investigate their decisions concerning whether to adopt blockchain technology and whether to invest in green technology. According to the selling format in the supply chain, this paper divides the research into two scenarios: Scenario R and Scenario A, to specify the supply chain members' optimal selections. In each scenario, all the strategy combinations of the green investment decisions and blockchain adoption are investigated in three modes by formulating a Stackelberg game model. For each modes, the tasks performed are as follows. Firstly, consumer's utility functions are constructed, and the demand functions are then obtained. Secondly, the manufacturer's and platform's profit functions are built and then the equilibrium solutions of each mode are determined. Following this, a sensitive analysis ensures, delving into the supply chain member's optimal wholesale and retail prices, carbon reduction level and information traceability level.

By examining the supply chain member's optimal decisions, this paper has some major findings:

- The manufacturer prefers to invest in green technology rather than taking no action, which indicates that, the manufacturer always obtains more profits in Mode RT/AT than in Mode RN/AN.
- The platform's decision on whether to adopt blockchain technology depends on consumer's acceptance of products. When consumer's acceptance of products is low and moderate, the platform prefers not to adopt blockchain, *i.e.*, Mode RT/AT. However, when consumer's acceptance of products is high, blockchain adoption is preferred by the platform, *i.e.*, Mode RB/AB.
- Two parameters play decisive roles in the manufacturer's and the platform's decisions: the consumer's acceptance of products and the consumer's environmental sensitivity. As the consumer's acceptance of products increases, the manufacturer's and the platform's choices both change from Mode RN/RT (Mode AN/AT) to Mode RB (Mode AB). And as the consumer's environmental sensitivity increases, their preferences change opposite, that is, from Mode RB (Mode AB) to Mode RN/RT (Mode AN/AT).
- The manufacturer's and the platform's mode choices are always analogous. When the consumer's acceptance of products is high, Mode RB/AB is preferred by the manufacturer and the platform. That is, they both

[4] https://newwezhanoss.oss-cn-hangzhou.aliyuncs.com/contents/sitefiles2035/10175544/files/180278.

expect to develop green technology to reduce carbon emission and adopt blockchain technology to disclose information. When this parameter is low and moderate, both of the manufacturer and platform prefer Modes RT/AT.

The study makes the following major contributions.

- To the best of our knowledge, this paper is the first to investigate the joint decision of the manufacturer and the platform in the context of sustainable development and blockchain era. This paper obtains some interesting findings that not only contribute to the existing literature related to blockchain adoption, but also provide some important managerial insights to the relevant practitioners on sustainable supply chain management.
- This paper, considering consumer's perception of carbon emission, blockchain technology, discusses consumer's acceptance of products, environmental sensitivity and preference for information disclose by blockchain on the supply chain member's decisions. This research perspective bridges research gap between supply chain management and consumer perception, which has not been considered in previous literature.
- Finally, important conclusions, such as that the manufacturer and platform have analogous preference in different scenarios, are obtained, which are insightful for promoting blockchain application in the context of sustainable supply chain management.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and discusses the connections between this study and previous research. In Sections 3 and 4, the paper introduces the model, analyzes the six operational modes across the two scenarios, and derives the equilibrium outcomes. Section 5 investigates the optimal decisions for both the manufacturer and the platform, addressing the primary research questions. Finally, Section 6 presents the conclusions, offers managerial insights based on the findings, and suggests directions for future research.

2. Literature review

This study is related to the existing literature in three streams of research: (i) green investment and sustainability; (ii) blockchain technology and information disclosure, (iii) supply chain operations with reselling and agency selling formats. But it also deviates from the existing literature in some essential aspects.

2.1. Green investment and sustainability

This study belongs to the research line of green investment and sustainability. Several scholars are interested in sustainability and financial performance in the supply chain management. In the seminal work of Clark *et al.* [15], they explore the relationship between sustainability and financial performance. Their findings suggest that integrating sustainability factors into investment decisions can lead to better financial outcomes, supporting the notion that sustainability goes beyond social responsibility and has tangible economic benefits. Eccles *et al.* [16] investigate the impact of corporate sustainability practices on organizational processes and financial performance. They find that firms with strong sustainability practices exhibit improved operational efficiency, risk management, and financial performance, providing evidence for the business case of sustainability. Yunis *et al.* [55] examine the relationship between green investment, firm value, and financial performance in emerging markets. Their findings indicate a positive association between green investment and firm value, underscoring the potential financial benefits of environmental commitment.

Other researchers concentrate on green investment and investment strategies. Horvath and Krick [21] provide a comprehensive survey on the definitions, organizations, and investment strategies involved in sustainable investing. Their review contributes to a better understanding of the evolving landscape of sustainable investment, emphasizing the diversity of approaches and actors within this field. Scholtens [42] conducts a literature review on integrating environmental considerations into financial decision-making processes. The study highlights the importance of incorporating environmental factors into financial decisions and discusses barriers and opportunities for further integration, contributing to the understanding of sustainable finance. Besides, other

paper focuses on corporate sustainability practices and organizational processes. Hawn and Ioannou [20] explore the interplay between external stakeholder pressures and internal firm actions in the context of corporate social responsibility (CSR). Their research sheds light on how external pressures and internal motivations interact to shape CSR practices within organizations.

Moreover, several scholars have focused on supply chain optimization and sustainability within specific contexts. Tirkolaee *et al.* [50] develop a novel mathematical model to design a sustainable closed-loop supply chain for masks during the COVID-19 outbreak, aiming to minimize total costs, pollution, and human risk. Similarly, Mondal and Roy [35] investigate a multi-objective, multi-product, multi-period supply chain planning model to ensure the continuous supply of resources between production centers and hospitals during the pandemic. Shokouhifar *et al.* [45] propose a mathematical model for designing a closed-loop food supply chain network, with the goal of minimizing both economic and exergetic costs. Mardani *et al.* [34] apply structural equation modeling to assess sustainable and green supply chain management practices. Hamidoğlu *et al.* [19] explore the establishment of a collaborative market environment involving farmers, agricultural enterprises, and consumers, examining their willingness to adopt low-carbon practices in response to market prices and government policies. Mukherjee *et al.* [37] incorporate repairable defective products into an uncertain supply chain environment, evaluating and validating the impact of four carbon taxation policies across various real-world scenarios, while also exploring the sensitivity of key parameters. Other studies, such as those by Paul *et al.* [38], Ali *et al.* [2], and Mondal *et al.* [36], also address issues related to supply chain sustainability and management. However, these studies often focus on specific industries, production environments, or product types, and may not fully consider the diverse needs of different sectors or organizations of varying sizes. Moreover, there is a lack of comprehensive assessments of the long-term benefits and sustainability impacts of green investments, underscoring the need for more empirical research to complement theoretical models.

The existing literature suggests that integrating sustainability factors into investment decisions can drive financial outperformance, enhance organizational processes and performance, and contribute to firm value. Furthermore, these reviews emphasize the importance of incorporating environmental considerations into financial decision-making and highlight the complex dynamics that shape corporate social responsibility (CSR) practices. However, most of this research primarily focuses on the financial dimensions of green investment and sustainability, particularly the relationship between sustainability practices and financial performance. It often overlooks other critical aspects, such as the social and environmental impacts, policy implications, and the role of stakeholder engagement.

In contrast, our paper contributes to the growing body of research on green investment and sustainability by focusing on the manufacturer's environmental concerns, specifically the carbon emissions generated during the production process, which can be mitigated through green investment. While few studies have examined the manufacturer's incentives to invest in environmentally friendly technologies across different supply chain structures, our research bridges this gap. We provide actionable insights for manufacturers, offering constructive suggestions for enhancing environmental protection through strategic green investments (Tab. 1).

2.2. Blockchain technology and information disclosure

This paper also falls into the research stream of the application of blockchain technology in the supply chain. Blockchain technology has been applied and developed in many industries, such as finance and supply chain management [4, 39, 59]. Goli *et al.* [18] discuss the role of blockchain technology toward a sustainable energy future, including technology, organizations and people, and the impacts during emergency situations and economic uncertainties. Recently, Iansiti and Lakhanl [24] discuss the fundamental features of blockchain and identified some applications in the digital world. Specifically, blockchain can distribute ledgers that can be verified, stored, and easily shared, and smart contracts are a potential application of this technology [14,41]. Bai and Sarkis [5] apply blockchain technology to increase transparency in sustainable supply chains and evaluated blockchain selection decisions by developing a group decision making model. In addition, Choi *et al.* [13] develop a monopoly model of Nash game between two platforms with price as an exogenous parameter, and derived a balanced product information disclosure strategy when implementing blockchain technology.

TABLE 1. Summary of the relevant literature.

Articles	Selling format	Supply chain structure	Carbon emission	Blockchain technology	Environment analysis
Barman *et al.* [7]	Reselling	One reseller and one manufacture	✓		✓
Barman *et al.* [6]	/	One manufacturer	✓		✓
Barman *et al.* [8]	/	/	✓		✓
Bhunia *et al.* [9]	/	/	✓		✓
Li *et al.* [28]	/	/	✓	✓	✓
Ma *et al.* [33]	Agency selling, reselling	One online platform and one manufacture		✓	✓
Zhang *et al.* [58]	/	One OEM and one TPR	✓	✓	✓
Huang *et al.* [23]	Agency selling, reselling	One e-Commerce platform and one manufacture		✓	
Zhao *et al.* [60]	Agency selling, reselling	One platform and one manufacture		✓	
Lu *et al.* [31]	/	One supplier, one online retailer, one offline retailer		✓	
Liu *et al.* [30]	Reseller, market	An individual manufacturer and an individual e-platform		✓	✓
Xu *et al.* [53]	Marketplace, reselling	A manufacturer and an online platform	✓	✓	✓
This paper	Agency selling, reselling	One platform and one manufacture	✓	✓	✓

Product information disclosure is a hot topic in practice and academic fields, and effective disclosure of product information is an effective way to solve consumer uncertainty. Therefore, many studies focus on information disclosure strategies. Zimmer *et al.* [61] propose an information disclosure model to achieve retailers' competitive advantage by satisfying consumer demand. Shulman *et al.* [46] find that companies may benefit from disclosing less information. In addition, by constructing a disclosure model in a dynamic sequential screening environment, Zhang *et al.* [57] show that companies can benefit from disclosing more information if the associated disclosure costs are reduced. Different from the above work, this paper considers the manufacturer to reduce carbon emissions of products, and the retail platform use blockchain technology to disclose manufacturer's carbon emission reduction information to consumers. Babaei *et al.* [3] focus on blockchain technology to design innovative and environmentally-friendly supply chain network with two-step authentication.

This paper differs from the above literature in two aspects. This paper analyzes whether the platform will adopt blockchain technology based on the consideration of carbon reduction decision taken by manufacturer. Besides, this paper assumes that retail platform has an incentive to adopt blockchain technology to disclose the carbon reduction information of products and bear the corresponding adoption costs. The literature has proposed the use of blockchain technology to improve the transparency and sustainability of supply chains, but may not have fully considered the costs of implementing these technologies. The literature has proposed the use of blockchain technology to improve the transparency and sustainability of supply chains, but may not have fully considered the costs of implementing these technologies. The literature has proposed the use of blockchain technology to improve the transparency and sustainability of supply chains, but may not have fully considered the costs of implementing these technologies.

2.3. Supply chain operations with different selling formats

Some papers focus on understanding and analyzing the dynamics of supply chain operations in the context of reselling and agency selling formats. Some scholars have studied the role of sales model in promoting coordination between upstream and downstream members of the supply chain, and analyzed the impact on the overall performance of the supply chain. Yao *et al.* [54] examine supply chain coordination under agency selling and reselling formats. Their study explores the implications of price commitment agreements on achieving coordination in such supply chains and highlights the impacts of pricing strategies on supply chain performance. Abhishek *et al.* [1] analyze the strategic sourcing decisions of wholesalers and their impact on downstream retailers and overall supply chain performance. They explore how wholesalers build sustainable supply chains, compete on quality, and establish advantageous relationships with retailers through sourcing strategies. Huang *et al.* [22] examine the coordination challenges in a two-echelon supply chain involving reselling, trade-in programs, and agency selling. They propose coordination mechanisms and strategies to enhance supply chain performance.

In addition, some scholars pay attention to the interaction between competition and sales model in supply chain. Chen *et al.* [10] investigate the competition dynamics among online sellers involved in agency selling and reselling. They explore the impact of information updating on competition outcomes, shedding light on the strategic choices made by sellers in the realm of online agency selling and reselling. Shen *et al.* [43] develop a supply chain model encompassing a manufacturer, a platform retailer, and a traditional reseller. The platform retailer assumes the role of a channel leader, possessing sufficient power to dictate contractual terms such as the revenue-sharing rate and slotting fee. This study discusses the optimal determination of the revenue-sharing rate by the platform retailer and the manufacturer's decision between adopting a dual-channel or sole-channel approach. Shen *et al.* [44] propose a stylized model featuring one manufacturer and two retailers. The dominant retailer commands a significantly larger market coverage and possesses the flexibility to choose its preferred selling format. In contrast, the weaker retailer's influence is limited to setting the retail price. The study examines the dominant retailer's choice between functioning as a platform retailer or a reseller, as well as the manufacturer's decision regarding channel selection.

Different from the aforementioned work, this paper based on the background of supply chain sustainability, dividing the research content into two scenarios according to the selling format: Scenarios R and A. And this paper analyses the impacts of the selling format on whether the manufacturer conducts carbon emission reduction and whether the platform adopts blockchain technology to disclose relevant information.

3. Model setting

This paper considers a supply chain in which a manufacturer ("he" in the following paper) could sell products to consumers through an online platform ("she" in the following paper). The manufacturer and the platform could cooperate in reselling or agency selling format. This supply chain structure is very common in practice. For example, Apple sells iPhone and iPad on TMALL in Apple's flagship store but sells on JD.com through JD's official self-running store. The main difference of these two selling formats is whether the manufacturer or the platform decides the retail price of the products. In the reselling format, the manufacturer wholesales products to platform with w and the platform resells to consumers in retail price p which indicates that the platform controls the pricing power in this format. While in agency selling format, the manufacturer directly sells products to consumers with retail price p and pays for the platform a commission fee γ which is a proportion of his profits. Thus, the manufacturer retains the pricing power himself in this format.

Consumers are environmental friendly who care about the greenness of the products, and are sensitive to the carbon emission. The manufacturer decides whether to invest in green technology or not, through which can reduce the carbon emission level of the products. Without green investment, the consumer's utility function can be written as

$$U = \theta v - p - \eta \cdot e_0,$$

where v is consumer's valuation of the manufacturer's products which uniformly distributes between 0 and 1, that is, $v \sim U[0,1]$. Consumers are environmentally friendly, θ represents consumer's acceptance degree for the products, which depends on whether the products are environmental or not. When the manufacturer doesn't invest in green technology, consumer's acceptance of the product is lower, that is, $0 < \theta < 1$. And consumer's acceptance $\theta = 1$ when the consumers realize that the products are green, that is, the manufacturer invests in green technology. η is consumer's sensitivity of carbon emission. e_0 represents the initial carbon emission level of the products without green green investment. Thus, when the manufacturer invests in green technology to reduce carbon emission with level e, consumer's the utility function is

$$U = \theta v - p - \eta \cdot (e_0 - e).$$

e is the level of carbon emission abatement after the manufacturer's investment in green technology, $e_0 - e$ shows the ultimate carbon emission level after green investment. Consumers cannot identify the greenness of the products. That is to say, the manufacturer's behavior to invest in green technology cannot be informed to the consumers. This may impact the sales of the products for that the consumers are environmental friendly and hurt the platform's profitability eventually. To overcome this problem, the platform adopts blockchain technology to disclose the information about the products to consumers. The adoption of blockchain technology can significantly improve the consumers' utility through three ways. Firstly, through blockchain technology, the platform can clearly inform the consumers that the manufacturer invest in green technology. Thus, the consumers realize that the products are green and their acceptance degree θ is improved to 1. Secondly, through the blockchain technology, the product's carbon abatement level e is revealed to the consumer. Finally, blockchain technology can enhance the level of product traceability, *i.e.*, I. Once blockchain technology is adopted, the platform needs to decide the product traceability level, denoted as I, which shows the scale and scope of product information. In general, when providing more information about product traceability, the customer's utility increases by $\alpha \cdot I$, where α represents the consumer's preference for the product's traceability information. In this context, consumer's utility function can be shown as

$$U = v - p - \eta \cdot (e_0 - e) + \alpha \cdot I,$$

where α represents the consumer's preference for the information disclosed by the platform.

Consumers will make purchase when the utility of buying a product is larger than not buying. We obtain the consumer's demand of products in different modes

$$\begin{aligned} d_{\mathrm{N}} &= 1 - \frac{\eta \cdot e_0 + p}{\theta}, \\ d_{\mathrm{T}} &= 1 - \frac{\eta \cdot (e_0 - e) + p}{\theta}, \\ d_{\mathrm{B}} &= 1 - \eta \cdot (e_0 - e) + \alpha \cdot I - p, \end{aligned}$$

where the superscripts N, T, B represent three different modes in this paper: without green investment and blockchain adoption, with green investment but without blockchain adoption, with green investment and blockchain adoption. What's more, the manufacturer's investment cost in carbon abatement is $\frac{1}{2}e^2$ and the platform's cost in information disclosure through blockchain technology is $\frac{1}{2}I^2$. The manufacturer's and platform's costs concavely increase with carbon abatement level and information disclosure level, respectively. Here, a quadratic cost function implies that it is increasingly more costly to exert more effort to reduce carbon emission and provide product information. The notations involved are presented in Table 2. According to the selling format in the supply chain, this paper constructs two scenarios: Scenario R and Scenario A. In each scenario, considering whether the manufacturer invests in green technology and whether the platform adopts blockchain technology to disclose environmental information, this papers build three different modes: Mode RN, Mode RT, Mode RB, and Mode AN, Mode AT, Mode AB, which represents no investment and no blockchain adoption,

TABLE 2. Notations and descriptions.

Notation	Description
Parameters	
γ	Commission fee charged by the platform.
θ	Consumer's acceptance of the products, $0 < \theta < 1$.
v	Consumer's valuation of the products, $v \sim U[0,1]$.
η	Consumer's sensitivity of carbon emission.
α	Consumer's preference for the product's traceability information.
e_0	The initial carbon emission level of the products without green green investment.
d	Consumer's demand for the products.
U	Consumer's utility function.
$\pi_{\mathrm{M}}, \pi_{\mathrm{P}}$	Profit functions of the manufacturer and platform.
Decision variables	
e	The level of carbon emission abatement after the manufacturer's investment in green technology.
I	The level of product traceability information provided by blockchain technology.
p	Retail price of the products.
w	Wholesale price of the products.

with green investment and no blockchain, with investment and blockchain technology. In total, there are six modes, we explain them as follows:

Scenarios R: the manufacturer and platform cooperated in reselling format,

(a) Mode RN: neither of the manufacturer and the platform take actions, their profit functions can be shown as $\pi_{\mathrm{M}}^{\mathrm{RN}} = w \cdot d_{\mathrm{N}}$, $\pi_{\mathrm{P}}^{\mathrm{RN}} = (p-w) \cdot d_{\mathrm{N}}$.
(b) Mode RT: the manufacturer invests in green technology, but the platform doesn't apply blockchain technology, their profit functions are $\pi_{\mathrm{M}}^{\mathrm{RT}} = w \cdot d_{\mathrm{T}} - \frac{1}{2}{e_{\mathrm{T}}}^2$, $\pi_{\mathrm{P}}^{\mathrm{RT}} = (p-w) \cdot d_{\mathrm{T}}$.
(c) Mode RB: the manufacturer invests in green technology, and the platform apply blockchain technology to disclose information, their profit functions are $\pi_{\mathrm{M}}^{\mathrm{RB}} = w \cdot d_{\mathrm{B}} - \frac{1}{2}e^2$, $\pi_{\mathrm{P}}^{\mathrm{RB}} = (p-w) \cdot d_{\mathrm{B}} - \frac{1}{2}I^2$.

Scenarios A: the manufacturer and platform cooperated in agency selling format,

(d) Mode AN: they both take no actions, their profit functions are $\pi_{\mathrm{M}}^{\mathrm{AN}} = (1-\gamma) \cdot p \cdot d_{\mathrm{N}}$, $\pi_{\mathrm{P}}^{\mathrm{AN}} = \gamma \cdot p \cdot d_{\mathrm{N}}$.
(e) Mode AT: only the manufacturer takes actions in green technology investment, the platform takes no action, the profit functions are given by $\pi_{\mathrm{M}}^{\mathrm{AT}} = (1-\gamma) \cdot p \cdot d_{\mathrm{T}} - \frac{1}{2}e^2$, $\pi_{\mathrm{P}}^{\mathrm{AT}} = \gamma \cdot p \cdot d_{\mathrm{T}}$.
(f) Mode AB: they both take actions, and we obtain their profit functions as $\pi_{\mathrm{M}}^{\mathrm{AB}} = (1-\gamma) \cdot p \cdot d_{\mathrm{B}} - \frac{1}{2}e^2$, $\pi_{\mathrm{P}}^{\mathrm{AB}} = \gamma \cdot p \cdot d_{\mathrm{B}} - \frac{1}{2}I^2$.

The channel structure and interactions between the manufacturer and platforms are shown in Figure 1. The sequence of events for each mode of operation is described as follows:

(a) Mode RN: in this benchmark mode, the manufacturer first decides the wholesale price w_{RN} of the products and then the platform sets the retail price p_{RN} to consumes.
(b) Mode RT: the decision sequence in this mode is as follows. First, the manufacturer decides the carbon abatement level e_{RT}, which incurs a cost of $\frac{1}{2}{e_{\mathrm{RT}}}^2$. Then, the manufacturer sets the wholesale price w_{RT} to the platform and the platform sets the retail price p_{RT} to consumers, eventually.
(c) Mode RB: the manufacturer first decides the carbon abatement level e_{RB} at a cost of $\frac{1}{2}{e_{\mathrm{RB}}}^2$. And then the platform decides the information disclosure level I_{RB} at a cost of $\frac{1}{2}{I_{\mathrm{RB}}}^2$. Next, the manufacturer and the platform sequentially decide the wholesale price w_{RB} and retail price p_{RB}.
(d) Mode AN: the manufacturer decides the retail price p_{AN} to consumers directly.
(e) Mode AT: the manufacturer invests in green technology to reduce the carbon emission and decides the carbon abatement level e_{AT}. Then the manufacturer decides the retail price p_{AT}.

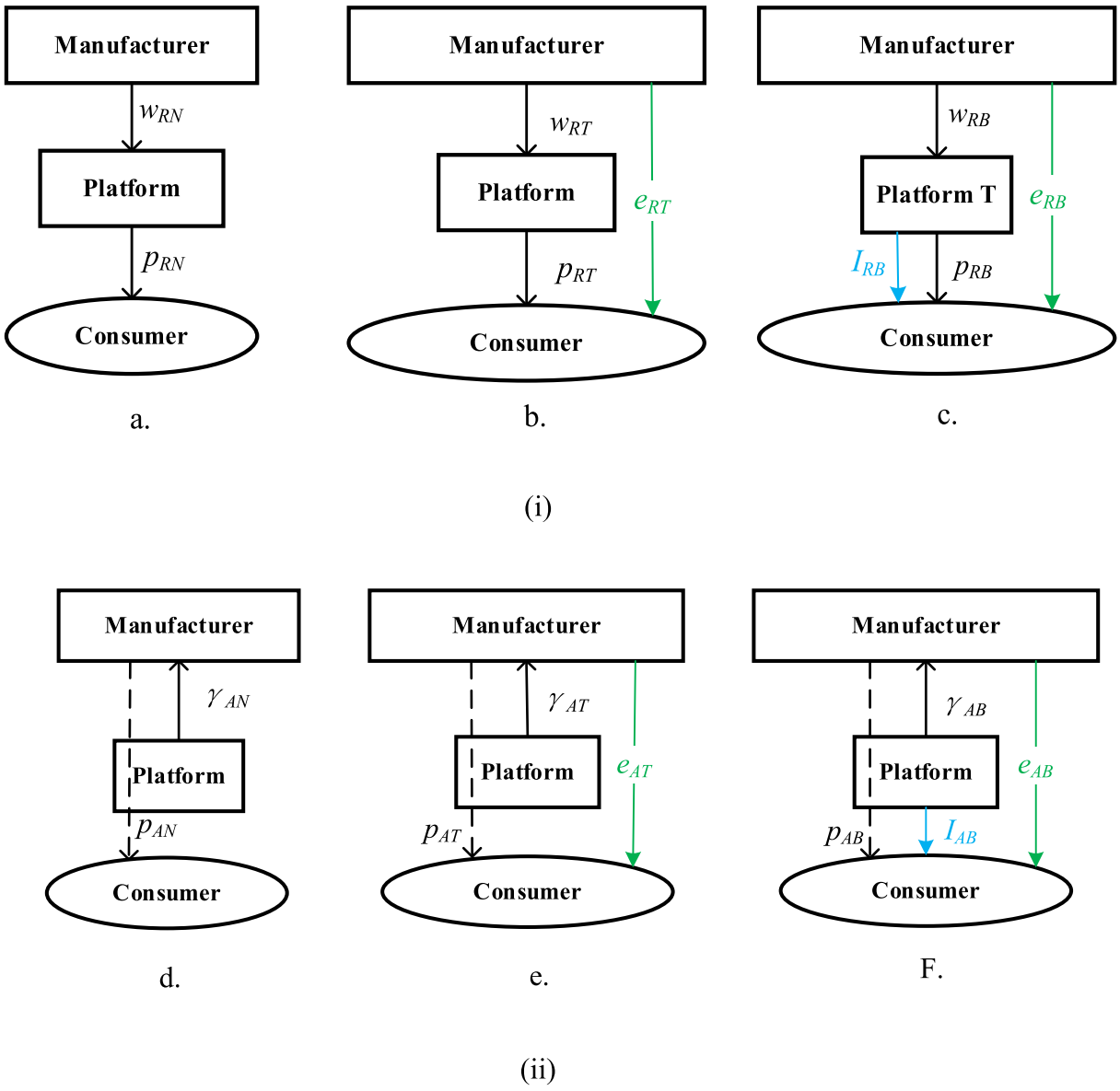


FIGURE 1. Channel structures. (i) Scenario R: (a) Model RN, (b) Model RT, (c) Model RB. (ii) Scenario A: (a) Model AN, (b) Model AT, (c) Model AB.

(f) Mode AB: the manufacturer invests in green technology to carry out carbon abatement at a level of e_{AB} with a cost of $\frac{1}{2}{e_{\mathrm{AB}}}^2$. Then the platform deploys blockchain technology to disclose environmental information I_{AB} with a cost of $\frac{1}{2}{I_{\mathrm{AB}}}^2$. Then, the manufacturer decides the retail price p_{AB}.

4. EQUILIBRIUM RESULTS

In this section, this paper first displays the detailed model settings in Scenarios R and A, and then calculate the equilibrium results of three modes in two different scenarios. Because this dynamic game contains multiple

rounds of strategic interactions, backward induction is applied to derive the subgame perfect equilibrium in this paper.

4.1. Scenario R: reselling format

In this scenario, the manufacturer cooperates with the platform through reselling format. In this format, the manufacturer wholesales the products to platform and the platform resells the products to consumers. According to whether the manufacturer invests in green technology and the platform adopts blockchain technology, this paper divides this scenario into three modes: Modes RN, RT and RB.

4.1.1. Mode RN: without green investment and blockchain adoption

In this mode, the manufacturer doesn't invest in green technology to reduce carbon of products. Thus, there is no initiative for the platform to adopt blockchain technology to disclosure related information. Thus, the manufacturer's and the platform's profit functions are shown below:

$$\pi_{\mathrm{M}}^{\mathrm{RN}} = w \cdot d_{\mathrm{N}} = w_{\mathrm{RN}} \cdot \left(1 - \frac{\eta \cdot e_0 + p_{\mathrm{RN}}}{\theta}\right),$$
$$\pi_{\mathrm{P}}^{\mathrm{RN}} = (p - w) \cdot d_{\mathrm{N}} = (p_{\mathrm{RN}} - w_{\mathrm{RN}}) \cdot \left(1 - \frac{\eta \cdot e_0 + p_{\mathrm{RN}}}{\theta}\right).$$

Using backward induction solution, this paper obtains the equilibrium wholesale and retail prices in mode RN as follows:

$$w_{\mathrm{RN}}^{*} = \frac{\theta - \eta \cdot e_0}{2},$$
$$p_{\mathrm{RN}}^{*} = \frac{3(\theta - \eta \cdot e_0)}{4}.$$

The manufacturer's and platform's equilibrium profits are

$$\pi_{\mathrm{M}}^{\mathrm{RN}*} = \frac{(\theta - \eta \cdot e_0)^2}{8\theta},$$
$$\pi_{\mathrm{P}}^{\mathrm{RN}*} = \frac{(\theta - \eta \cdot e_0)^2}{16\theta}.$$

It can observed directly that the total profit is divided proportionally between the manufacturer and the platform. The wholesale and retail prices, the manufacturer's and the platform's profits are all positively related to the consumer's acceptance of products and negatively related to the product's carbon emission. This indicates that, the supply chain members should make efforts to improve the consumer's acceptance and reduce the product's carbon emission. These analyses give supports for the following conclusions in our paper.

4.1.2. Mode RT: with green investment but without blockchain adoption

In this mode, the manufacturer invests capital to carry out green investment, in order to reduce carbon emission in the productive process. The manufacturer's and platform's profit functions are showed below:

$$\pi_{\mathrm{M}}^{\mathrm{RT}} = w \cdot d_{\mathrm{T}} - \frac{1}{2}e^2 = w_{\mathrm{RT}} \cdot \left(1 - \frac{\eta \cdot (e_0 - e_{\mathrm{RT}}) + p_{\mathrm{RT}}}{\theta}\right) - \frac{1}{2}{e_{\mathrm{RT}}}^2,$$
$$\pi_{\mathrm{P}}^{\mathrm{RT}} = (p - w) \cdot d_{\mathrm{T}} = (p_{\mathrm{RT}} - w_{\mathrm{RT}}) \cdot \left(1 - \frac{\eta \cdot (e_0 - e_{\mathrm{RT}}) + p_{\mathrm{RT}}}{\theta}\right).$$

Through backward induction, this paper obtains the equilibrium results as follows in Proposition 1:

Proposition 1. *When satisfying* $4\theta - \eta^2 > 0$*, the equilibrium results in Mode RT are*

$$e_{\mathrm{RT}}^* = \frac{\eta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2},$$
$$w_{\mathrm{RT}}^* = \frac{2\theta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2},$$
$$p_{\mathrm{RT}}^* = \frac{3\theta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2}.$$

Thus, this paper derives the equilibrium profits of the manufacturer and the platform

$$\pi_{\mathrm{M}}^{\mathrm{RT}*} = \frac{1}{2(4\theta - \eta^2)}(\theta - \eta \cdot e_0)^2,$$
$$\pi_{\mathrm{P}}^{\mathrm{RT}*} = \frac{\theta}{(4\theta - \eta^2)^2}(\theta - \eta \cdot e_0)^2.$$

It is obviously that the total profits still proportionally distribute between the manufacturer and the platform as same as in Mode RN. Resorting to sensitive analyses, this paper derives Lemma 1.

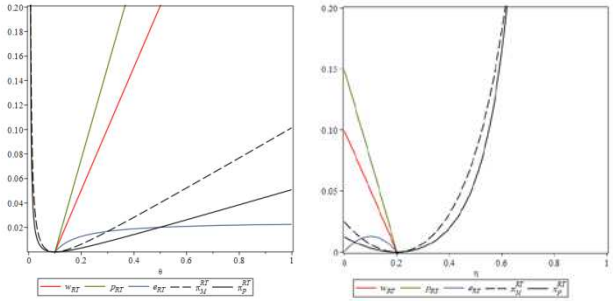
Lemma 1. *The following are sensitive analyses of the decision variables in Mode RT with respect to consumer's acceptance* (θ)*:*

(1) $\frac{\partial e_{\mathrm{RT}}^*}{\partial \theta} > 0$ *if* $\eta \le 4e_0$, $\frac{\partial e_{\mathrm{RT}}^*}{\partial \theta} < 0$ *if* $\eta > 4e_0$*; when* $\eta \le 4e_0$, $\frac{\partial w_{\mathrm{RT}}^*}{\partial \theta} > 0$ *and* $\frac{\partial p_{\mathrm{RT}}^*}{\partial \theta} > 0$*. When* $\eta > 4e_0$, $\frac{\partial w_{\mathrm{RT}}^*}{\partial \theta} < 0$ *and* $\frac{\partial p_{\mathrm{RT}}^*}{\partial \theta} < 0$ *if* $\frac{1}{4}(\eta^2 - \eta\sqrt{\eta^2 - 4\eta e_0}) < \theta < \frac{1}{4}(\eta^2 + \eta\sqrt{\eta^2 - 4\eta e_0})$*, otherwise,* $\frac{\partial w_{\mathrm{RT}}^*}{\partial \theta} \ge 0$ *and* $\frac{\partial p_{\mathrm{RT}}^*}{\partial \theta} \ge 0$*. When* $\eta \le 2e_0$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \theta} > 0$*; when* $\eta > 2e_0$. $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \theta} < 0$ *if* $\theta < \frac{1}{2}\eta(\eta - e_0)$*, otherwise,* $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \theta} > 0$*. When* $\frac{4}{9}e_0 \le \eta \le 4e_0$, $\frac{\pi_{\mathrm{P}}^{\mathrm{RT}*}}{\partial \theta} \le 0$*; when* $\eta < \frac{4}{9}e_0$ *and* $\eta > 4e_0$, $\frac{\pi_{\mathrm{P}}^{\mathrm{RT}*}}{\partial \theta} > 0$ *if* $\frac{1}{8}(3\eta - 4e_0 - \sqrt{9\eta^2 - 40\eta e_0 + 16{e_0}^2}) < \theta < \frac{1}{8}(3\eta - 4e_0 + \sqrt{9\eta^2 - 40\eta e_0 + 16{e_0}^2})$.

(2) *When* $\eta \le 8e_0$, $\frac{\partial e_{\mathrm{RT}}^*}{\partial \eta} \le 0$*; when* $\eta > 8e_0$, $\frac{\partial e_{\mathrm{RT}}^*}{\partial \eta} > 0$ *if* $\theta < \frac{1}{4}\eta(\eta - 8e_0)$ *and negative otherwise. When* $0 < e_0 \le \frac{2\theta\eta}{\eta^2 + 4\theta}$, $\frac{\partial w_{\mathrm{RT}}^*}{\partial \eta} \ge 0$, $\frac{\partial p_{\mathrm{RT}}^*}{\partial \eta} \ge 0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{RT}*}}{\partial \eta} \ge 0$*; when* $\frac{2\theta\eta}{\eta^2 + 4\theta} < e_0 < 1$, $\frac{\partial w_{\mathrm{RT}}^*}{\partial \eta} < 0$, $\frac{\partial p_{\mathrm{RT}}^*}{\partial \eta} < 0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{RT}*}}{\partial \eta} < 0$*. When* $\eta \ge 4e_0$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \eta} \ge 0$ *if* $\theta \le \eta e_0$ *and* $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \eta} < 0$ *otherwise; when* $\eta < 4e_0$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \eta} \le 0$ *if* $\theta \le \eta e_0$ *and* $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \eta} > 0$ *otherwise.*

It can be easily verified that the carbon abatement level changes with the consumer's acceptance of products depending on the relative relationship between e_0 and η. When $\eta < 4e_0$, the manufacturer have more initiative to invest in green technology when consumer's acceptance increases. When $\eta \ge 4e_0$, the manufacturer is less likely to invest in green technology as consumer's acceptance increases. The wholesale and retail prices both increase with θ. Besides, the increase of θ first decreases and then increases the manufacturer's profit, the threshold is $\theta > \frac{1}{2}\eta(\eta - 2e_0)$. When $\theta < \frac{1}{8}(3\eta - 4e_0 + \sqrt{9\eta^2 - 40\eta e_0 + 16{e_0}^2})$, the platform's profit is decreasing in θ. These indicate that the manufacturer's and the platform's profits does not monotonously change with the consumer's acceptance of products. When it comes to consumer's environmental sensitivity, the carbon abatement level, wholesale and retail prices and the manufacturer's profits are all firstly decrease and then increase with the increasing of η. However, the platform's profit presents the opposite tendency. This indicates that the manufacturer's incentive is not always aligned with the platform's.

We resorts to numerical analyses to investigate the impacts of consumer's acceptance of products (θ) and consumer's environmental sensitivity (η). The equilibrium results in Mode RT changes with θ are shown in Figure 2A. It is obvious that, when parameters are set $e_0 = 1$, $\eta = 0.1$ and $\alpha = 0.2$, the equilibrium wholesale price, retail price and carbon abatement level all increase as θ increases. This is due to the consumer's increasing acceptance of products brings more market demand which gives the supply chain members more initiative to



(a) (b)

FIGURE 2. Variations in the equilibrium results in Scenario RT with respect to θ and η: $e_0 = 1$. (A) $\eta = 0.1, \alpha = 0.2$. (B) $\eta = 0.2, \alpha = 0.2$.

charge higher prices. The manufacturer's carbon abatement level is also increasing with θ but the increase is slowing down as θ becomes larger. Besides, the manufacturer's and the platform's profits are first decreasing and then increasing with θ. When the consumer's acceptance is very low, the manufacturer has no motivation to invest in carbon abatement cutting down the consumer's purchasing desire and resulting in decreasing profits. When consumer's acceptance increases, the manufacturer invests in carbon abatement which brings higher consumer purchasing desire and results in increasing profit for the manufacturer in reverse. The equilibrium results in Mode RT changes with η are shown in Figure 2B. The wholesale and retail prices are both decreasing with η which indicates that the platform should cut down her retail price to satisfy the consumer's higher environmental sensitivity. And the manufacturer would also decrease his wholesale price when the impact of the consumer's higher environmental sensitivity transfer to upstream supply chain. However, the carbon abatement level presents a first increasing and then decreasing tendency with η. The manufacturer first invests in green technology for higher consumer preference but as the costs becomes larger, his initiative becomes smaller. What's more, the manufacturer's and the platform's profits both show a decreasing tendency when η is small. This is rational because of the lower wholesale and retail prices.

4.1.3. Mode RB: with green investment and blockchain adoption

In this mode, the manufacturer invests in green technology to reduce the carbon emission of the products. And the platform deploys blockchain technology to inform the consumers about the environmental information of the products. Thus, the manufacturer's and platform's profit functions are shown below:

$$\pi_{\mathrm{M}}^{\mathrm{RB}} = w \cdot d_{\mathrm{B}} - \frac{1}{2}e^2 = w_{\mathrm{RB}} \cdot [1 - \eta \cdot (e_0 - e_{\mathrm{RB}}) + \alpha \cdot I - p_{\mathrm{RB}}] - \frac{1}{2}{e_{\mathrm{RB}}}^2,$$
$$\pi_{\mathrm{P}}^{\mathrm{RB}} = (p - w) \cdot d_{\mathrm{B}} - \frac{1}{2}I^2 = (p_{\mathrm{RB}} - w_{\mathrm{RB}}) \cdot [1 - \eta \cdot (e_0 - e_{\mathrm{RB}}) + \alpha \cdot I - p_{\mathrm{RB}}] - \frac{1}{2}{I_{\mathrm{RB}}}^2.$$

We derives the equilibrium results in this mode and display below in Proposition 2.

Proposition 2. *When satisfying and* $(\alpha^2 - 8)^2 - 16\eta^2 > 0$*, the equilibrium results in Mode RB are*

$$e_{\mathrm{RB}}^* = \frac{16\eta \cdot (1 - \eta \cdot e_0)}{(\alpha^2 - 8)^2 - 16\eta^2}$$
$$I_{\mathrm{RB}}^* = \frac{\alpha(\alpha^2 - 8) \cdot (\eta \cdot e_0 - 1)}{(\alpha^2 - 8)^2 - 16\eta^2},$$
$$w_{\mathrm{RB}}^* = \frac{4(\alpha^2 - 8) \cdot (\eta \cdot e_0 - 1)}{(\alpha^2 - 8)^2 - 16\eta^2},$$

$$p_{\mathrm{RB}}^{*}=\frac{6\left(\alpha^{2}-8\right)\cdot\left(\eta\cdot e_{0}-1\right)}{\left(\alpha^{2}-8\right)^{2}-16\eta^{2}}.$$

Substituting these equilibrium results in the profits functions, this paper obtains the manufacturer's and the platform's equilibrium profits as follows:

$$\pi_{\mathrm{M}}^{\mathrm{RB}*}=\frac{8\left(\eta\cdot e_{0}-1\right)^{2}}{\left(\alpha^{2}-8\right)^{2}-16\eta^{2}},$$
$$\pi_{\mathrm{P}}^{\mathrm{RB}*}=\frac{-\left(\alpha^{2}-8\right)^{3}\cdot\left(\eta\cdot e_{0}-1\right)^{2}}{2\left[\left(\alpha^{2}-8\right)^{2}-16\eta^{2}\right]^{2}}.$$

This paper resorts to sensitive analyses to explore how the equilibrium results and profits change with consumer's environmental sensitivity and consumer's preference for the environmental information, and exhibit the results in Lemma 2.

Lemma 2. *The following are sensitive analyses of the decision variables in Mode RB with respect to consumer's environmental sensitivity* (η) *and consumer's preference* (α) *for the environmental information:*

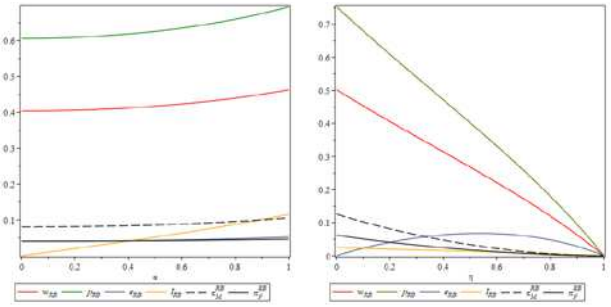
(1) $\frac{\partial e_{\mathrm{RB}}^{*}}{\partial\eta}>0$. *When* ${e_0}^2\left(\alpha^{2}-8\right)^{2}\geq 16$, $\frac{\partial I_{\mathrm{RB}}^{*}}{\partial\eta}\leq 0$, $\frac{\partial w_{\mathrm{RB}}^{*}}{\partial\eta}\leq 0$ *and* $\frac{\partial p_{\mathrm{RB}}^{*}}{\partial\eta}\leq 0$*; when* ${e_0}^2\left(\alpha^{2}-8\right)^{2}<16$, $\frac{\partial I_{\mathrm{RB}}^{*}}{\partial\eta}>0$, $\frac{\partial w_{\mathrm{RB}}^{*}}{\partial\eta}>0$, $\frac{\partial p_{\mathrm{RB}}^{*}}{\partial\eta}>0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{RB}*}}{\partial\eta}>0$ *if* $\frac{4+\sqrt{16-{e_0}^2\left(\alpha^{2}-8\right)^{2}}}{4e_0}<\eta<\frac{4-\sqrt{16-{e_0}^2\left(\alpha^{2}-8\right)^{2}}}{4e_0}$, *otherwise* $\frac{\partial I_{\mathrm{RB}}^{*}}{\partial\eta}<0$, $\frac{\partial w_{\mathrm{RB}}^{*}}{\partial\eta}<0$, $\frac{\partial p_{\mathrm{RB}}^{*}}{\partial\eta}<0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{RB}*}}{\partial\eta}<0$. *When* $\eta\geq\frac{1}{16}e_0\left(\alpha^{2}-8\right)^{2}$, $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{RB}*}}{\partial\eta}\geq 0$*; when* $\eta<\frac{1}{16}\left(\alpha^{2}-8\right)^{2}e_0$, $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{RB}*}}{\partial\eta}<0$. *When* $\eta\geq\frac{1}{2}e_0[\left(\alpha^{2}-8\right)^{2}+16\eta^{2}]$, $\frac{\pi_{\mathrm{P}}^{\mathrm{RB}*}}{\partial\eta}\leq 0$*; when* $\eta<\frac{1}{2}e_0[\left(\alpha^{2}-8\right)^{2}+16\eta^{2}]$, $\frac{\pi_{\mathrm{P}}^{\mathrm{RB}*}}{\partial\eta}>0$.

(2) $\frac{\partial e_{\mathrm{RB}}^{*}}{\partial\alpha}>0$, $\frac{\partial I_{\mathrm{RB}}^{*}}{\partial\alpha}>0$, $\frac{\partial w_{\mathrm{RB}}^{*}}{\partial\alpha}>0$, $\frac{\partial p_{\mathrm{RB}}^{*}}{\partial\alpha}>0$, $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{RB}*}}{\partial\alpha}>0$, $\frac{\pi_{\mathrm{P}}^{\mathrm{RB}*}}{\partial\alpha}>0$.

From Lemma 2(1) it can be observed that the manufacturer would invest more in carbon abatement as the consumer's environmental sensitivity increases. However, the platform's information disclosure level changes with the consumer's environmental sensitivity depending on the interaction between the carbon emission before green investment e_0 and the consumer's preference for the information α. When these two parameters are small, the platform will increase the information disclosed level when consumer's environmental sensitivity lies in the moderate level. But the platform would reduce the disclosed level when the consumer's environmental sensitivity is relatively low or high. These also apply to the wholesale and retail prices. When the consumer's environmental sensitivity is higher than a threshold, the manufacturer's profit would increase as η becomes larger. But the platform's profit shows the opposite tendency when η is higher. These hinges on the reason that the manufacturer and the platform take different actions when the consumer's environmental sensitivity is high. That is, the manufacturer invests more to reduce carbon emission which brings more consumer demand and raises the wholesale price. However, the platform decreases the information disclosed level, which hurts the consumer's utility and negatively impacts the retail price of the platform.

Lemma 2(2) shows that the manufacturer's carbon abatement level and the platform's information disclosure level are both increasing with the consumer's preference for the environmental information. This indicates that both the manufacturer and the platform have more incentive to take actions as consumers are more information sensitive about product's environmental impact. What's more, the platform will put up the retail price which brings her more profit as result. The platform's action gives the manufacturer chance to charge higher wholesale price to enhance his profit. Generally speaking, the consumer's preference for the environmental information would boost the manufacturer's and the platform's actions, which is beneficial for the whole supply chain's profitability. It is also worth noting that, the information environment is optimized which eliminate the consumer's concern about the products' environmental property.

The numerical analyses investigate the impacts of consumer's preference for environmental information disclosed by the platform (α) and consumer's environmental sensitivity (η). Figure 3A shows the changes in



(a) (b)

FIGURE 3. Variations in the equilibrium results in Scenario RB with respect to α and η: $e_0 = 1$. (A) $\eta = 0.1, \theta = 0.2$. (B) $\theta = 0.2, \alpha = 0.2$.

TABLE 3. Equilibrium results.

Modes	w	p	e	I	π_M	π_P
RN	$\frac{\theta - \eta \cdot e_0}{2}$	$\frac{3(\theta - \eta \cdot e_0)}{4}$	–	–	$\frac{(\theta - \eta \cdot e_0)^2}{8\theta}$	$\frac{(\theta - \eta \cdot e_0)^2}{16\theta}$
RT	$\frac{2\theta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2}$	$\frac{3\theta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2}$	$\frac{\eta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2}$	–	$\frac{(\theta - \eta \cdot e_0)^2}{2(4\theta - \eta^2)}$	$\frac{\theta(\theta - \eta \cdot e_0)^2}{(4\theta - \eta^2)^2}$
RB	$\frac{4(\alpha^2 - 8) \cdot (\eta \cdot e_0 - 1)}{(\alpha^2 - 8)^2 - 16\eta^2}$	$\frac{6(\alpha^2 - 8) \cdot (\eta \cdot e_0 - 1)}{(\alpha^2 - 8)^2 - 16\eta^2}$	$\frac{16\eta \cdot (1 - \eta \cdot e_0)}{(\alpha^2 - 8)^2 - 16\eta^2}$	$\frac{\alpha(\alpha^2 - 8) \cdot (\eta \cdot e_0 - 1)}{(\alpha^2 - 8)^2 - 16\eta^2}$	$\frac{8(\eta \cdot e_0 - 1)^2}{(\alpha^2 - 8)^2 - 16\eta^2}$	$\frac{-(\alpha^2 - 8)^3 \cdot (\eta \cdot e_0 - 1)^2}{2[(\alpha^2 - 8)^2 - 16\eta^2]^2}$
AN	–	$\frac{\theta - \eta \cdot e_0}{2}$	–	–	$\frac{(1 - \gamma) \cdot (\theta - \eta \cdot e_0)^2}{4\theta}$	$\frac{\gamma \cdot (\theta - \eta \cdot e_0)^2}{4\theta}$
AT	–	$\frac{\theta \cdot (\theta - \eta \cdot e_0)}{\eta^2(\gamma - 1) + 2\theta}$	$\frac{\eta(1 - \gamma) \cdot (\theta - \eta \cdot e_0)}{\eta^2(\gamma - 1) + 2\theta}$	–	$\frac{(1 - \gamma) \cdot (\theta - \eta \cdot e_0)^2}{2[\eta^2(\gamma - 1) + 2\theta]}$	$\frac{\gamma\theta \cdot (\theta - \eta \cdot e_0)^2}{[\eta^2(\gamma - 1) + 2\theta]^2}$
AB	–	$\frac{(\alpha^2\gamma - 2) \cdot (\eta \cdot e_0 - 1)}{(\alpha^2\gamma - 2)^2 - 2\eta^2(1 - \gamma)}$	$\frac{2\eta(1 - \gamma) \cdot (1 - \eta \cdot e_0)}{(\alpha^2\gamma - 2)^2 - 2\eta^2(1 - \gamma)}$	$\frac{\alpha\gamma(\alpha^2\gamma - 2) \cdot (\eta \cdot e_0 - 1)}{(\alpha^2\gamma - 2)^2 - 2\eta^2(1 - \gamma)}$	$\frac{(1 - \gamma) \cdot (\eta \cdot e_0 - 1)^2}{(\alpha^2\gamma - 2)^2 - 2\eta^2(1 - \gamma)}$	$\frac{-(\gamma(\alpha^2\gamma - 2))^3 \cdot (\eta \cdot e_0 - 1)^2}{2[(\alpha^2\gamma - 2)^2 - 2\eta^2(1 - \gamma)]^2}$

equilibrium results in Mode RB with α. It can be observed that, the wholesale and retail prices, the carbon abatement level and the information disclosure level all increase with α. What's more, the manufacturer's and the platform's profits are also increasing with α. As the consumers show growing preference for the environmental information, the platform decides to disclose more information about the carbon abatement level so as to cater the consumer's preference. Although more disclosed information brings the platform more cost which hurts her profits, the consumers generate more market demand which offsets the cost caused by information disclosure and improves the platform's profit. From Figure 3B, it can be found that the carbon abatement level shows a first increasing and then decreasing tendency with the changes of η. And the wholesale and retail prices, the information disclosure level all decrease with η. The rationale behind these results hinges on that when the consumer's environmental sensitivity is relatively low, the manufacturer's increasing investment in carbon abatement hurts his profits and this impact transfers to the downstream platform's profit. What's more, when the consumer's environmental sensitivity becomes higher, the lower level of carbon abatement would bring a larger decrease of the consumer's utility which hurts the demand and brings negative impacts on the manufacturer's and platform's profits (Tab. 3).

4.2. Scenario A: agency selling format

In this scenario, the supply chain members cooperate in agency selling format. In this format, the manufacturer directly sells products to consumers and the platform charges a proportion of the manufacturer's profit

which is called commission fee. This commission fee γ is exogenous in this paper, which is widely used in the previous literature.

4.2.1. Mode AN: without green investment and blockchain adoption

In this mode, neither the manufacturer invests in green technology nor the platform adopts blockchain technology. Thus, the manufacturer's and platform's profit functions are showed below:

$$\pi_{\mathrm{M}}^{\mathrm{AN}} = (1-\gamma)\cdot p\cdot d_{\mathrm{N}} = (1-\gamma)\cdot p_{\mathrm{AN}}\cdot\left(1-\frac{\eta\cdot e_0+p_{\mathrm{AN}}}{\theta}\right),$$
$$\pi_{\mathrm{P}}^{\mathrm{AN}} = \gamma\cdot p\cdot d_{\mathrm{N}} = \gamma\cdot p_{\mathrm{AN}}\cdot\left(1-\frac{\eta\cdot e_0+p_{\mathrm{AN}}}{\theta}\right).$$

This paper obtains the equilibrium retail price as

$$p_{\mathrm{AN}}^{*} = \frac{\theta-\eta\cdot e_0}{2}.$$

Substituting the equilibrium price into the manufacturer's and the platform's profits function, this paper obtains

$$\pi_{\mathrm{M}}^{\mathrm{AN}*} = \frac{(1-\gamma)\cdot(\theta-\eta\cdot e_0)^2}{4\theta},$$
$$\pi_{\mathrm{P}}^{\mathrm{AN}*} = \frac{\gamma\cdot(\theta-\eta\cdot e_0)^2}{4\theta}.$$

It can be observed that, the total profit is divided between the manufacturer and the platform according to the commission fee γ. What's more, the retail price and the supply chain members' profits are all increase with the consumer's acceptance of products. This indicates that, the manufacturer's investment on carbon abatement will benefit the supply chain operation which supports the following research of this paper.

4.2.2. Mode AT: with green investment but without blockchain adoption

In this mode, the manufacturer invests in green technology to reduce the carbon emission and decides the carbon abatement level e_{AT}. Then the manufacturer decides the retail price p_{AT}.

The manufacturer's and platform's profit functions are showed below:

$$\pi_{\mathrm{M}}^{\mathrm{AT}} = (1-\gamma)\cdot p\cdot d_{\mathrm{T}} - \frac{1}{2}e^2 = (1-\gamma)\cdot p_{\mathrm{AT}}\cdot\left(1-\frac{\eta\cdot(e_0-e_{\mathrm{AT}})+p_{\mathrm{AT}}}{\theta}\right) - \frac{1}{2}{e_{\mathrm{AT}}}^2,$$
$$\pi_{\mathrm{P}}^{\mathrm{AT}} = \gamma\cdot p\cdot d_{\mathrm{T}} = \gamma\cdot p_{\mathrm{AT}}\cdot\left(1-\frac{\eta\cdot(e_0-e_{\mathrm{AT}})+p_{\mathrm{AT}}}{\theta}\right).$$

Using backward induction solution, this paper obtains the equilibrium results shown in the following Proposition 3.

Proposition 3. *When satisfying $\eta^2(\gamma-1)+2\theta>0$, the equilibrium results in Mode AT are:*

$$e_{\mathrm{AT}}^{*} = \frac{\eta(1-\gamma)\cdot(\theta-\eta\cdot e_0)}{\eta^2(\gamma-1)+2\theta},$$
$$p_{\mathrm{AT}}^{*} = \frac{\theta\cdot(\theta-\eta\cdot e_0)}{\eta^2(\gamma-1)+2\theta}.$$

Then this paper obtains the equilibrium profits of the manufacturer and the platform

$$\pi_{\mathrm{M}}^{\mathrm{AT}*} = \frac{(1-\gamma)\cdot(\theta-\eta\cdot e_0)^2}{2[\eta^2(\gamma-1)+2\theta]},$$

$$\pi_{\mathrm{P}}^{\mathrm{AT}*} = \frac{\gamma\theta \cdot (\theta - \eta \cdot e_0)^2}{[\eta^2(\gamma-1) + 2\theta]^2}.$$

It is obvious that the profit distribution between the manufacturer and the platform is rearranged as a result of the manufacturer's action on carbon abatement. Through the sensitive analyses, this paper discusses the impact of consumer's acceptance of products and environmental sensitivity on the equilibrium results. This paper shows these analyses below in Lemma 3.

Lemma 3. *The following are sensitive analyses of the decision variables in Mode AT with respect to consumer's acceptance of products (θ) and environmental sensitivity (η):*

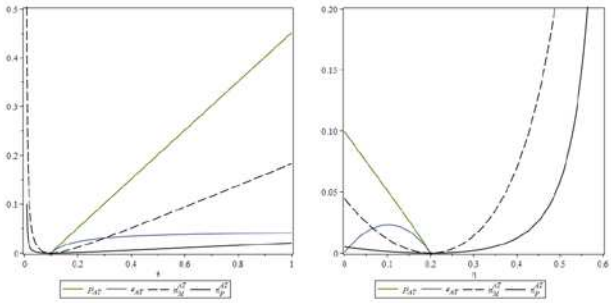
(1) $\frac{\partial e_{\mathrm{AT}}^*}{\partial\theta} > 0$. *When* $e_0 \le \frac{1}{2}\eta(1-\gamma)$, $\frac{\partial p_{\mathrm{AT}}^*}{\partial\theta} \ge 0$; *when* $e_0 > \frac{1}{2}\eta(1-\gamma)$, $\frac{\partial p_{\mathrm{AT}}^*}{\partial\theta} < 0$ *if* $\frac{1}{2}\{\eta(1-\gamma) - \sqrt{\eta(1-\gamma)[2e_0+\eta(1-\gamma)]}\} < \theta < \frac{1}{2}\{\eta(1-\gamma) - \sqrt{\eta(1-\gamma)[2e_0+\eta(1-\gamma)]}\}$, *otherwise* $\frac{\partial p_{\mathrm{AT}}^*}{\partial\theta} > 0$. *When* $e_0 \ge \eta(1-\gamma)$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}*}}{\partial\theta} \ge 0$; *when* $e_0 < \eta(1-\gamma)$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}*}}{\partial\theta} < 0$ *if* $\theta < \eta^2(1-\gamma) - \eta e_0$, *otherwise* $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}*}}{\partial\theta} > 0$. *When* $\eta(1-\gamma) \le 2e_0 \le 9\eta(1-\gamma)$, $\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial\theta} \ge 0$; *when* $2e_0 > 9\eta(1-\gamma)$ or $2e_0 < \eta(1-\gamma)$, $\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial\theta} < 0$ *if* $\frac{1}{4}\{3\eta(1-\gamma) - 2e_0 - \sqrt{9\eta^2(1-\gamma)^2 + 4e_0[e_0 - 5\eta(1-\gamma)]}\} < \theta < \frac{1}{4}\{3\eta(1-\gamma) - 2e_0 + \sqrt{9\eta^2(1-\gamma)^2 + 4e_0[e_0 - 5\eta(1-\gamma)]}\}$, *otherwise* $\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial\theta} > 0$.

(2) *When* $2{e_0}^2 \ge \theta(1-\gamma)$, $\frac{\partial e_{\mathrm{AT}}^*}{\partial\eta} \le 0$; *when* $2{e_0}^2 < \theta(1-\gamma)$, $\frac{\partial e_{\mathrm{AT}}^*}{\partial\eta} > 0$ *if* $\frac{2e_0 - \sqrt{4{e_0}^2 - 2\theta(1-\gamma)}}{1-\gamma} < \eta < \frac{2e_0 + \sqrt{4{e_0}^2 - 2\theta(1-\gamma)}}{1-\gamma}$, *otherwise,* $\frac{\partial e_{\mathrm{AT}}^*}{\partial\eta} \le 0$. *When* $2{e_0}^2 \le \theta(1-\gamma)$, $\frac{\partial p_{\mathrm{AT}}^*}{\partial\eta} \le 0$; *when* $2{e_0}^2 > \theta(1-\gamma)$, $\frac{\partial p_{\mathrm{AT}}^*}{\partial\eta} > 0$ *if* $\frac{\theta(1-\gamma) - \sqrt{\theta(1-\gamma)[\theta(1-\gamma) - 2{e_0}^2]}}{e_0(1-\gamma)} < \eta < \frac{\theta(1-\gamma) + \sqrt{\theta(1-\gamma)[\theta(1-\gamma) - 2{e_0}^2]}}{e_0(1-\gamma)}$, *otherwise* $\frac{\partial p_{\mathrm{AT}}^*}{\partial\eta} \le 0$. *When* $2e_0 \le \eta(1-\gamma)$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}*}}{\partial\eta} \ge 0$; *when* $2e_0 > \eta(1-\gamma)$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}*}}{\partial\eta} < 0$. *When* $2{e_0}^2 \le \theta(1-\gamma)$, $\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial\eta} \le 0$; *when* $2{e_0}^2 > \theta(1-\gamma)$, $\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial\eta} > 0$ *if* $\frac{\theta(1-\gamma) - \sqrt{\theta(1-\gamma)[\theta(1-\gamma) - 2{e_0}^2]}}{e_0(1-\gamma)} < \eta < \frac{\theta(1-\gamma) + \sqrt{\theta(1-\gamma)[\theta(1-\gamma) - 2{e_0}^2]}}{e_0(1-\gamma)}$, *otherwise* $\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial\eta} \le 0$.

It can be observed from Lemma 3(1) that, the manufacturer will invest more to reduce carbon emission level as consumer's acceptance of product increases. This result is different with the situation in Mode RT. Because in Mode AT, the manufacturer controls the final pricing power and only share with the platform a proportion of his profit. Thus, the manufacturer has more incentive to reduce the carbon emission to attract more consumer demand which offers the manufacturer probability to retain more profits himself. The retail price exhibit complex change tendency changing with θ, that is, it changes with the consumer's acceptance parameter depending on the initial carbon emission, consumer's environmental sensitivity and the commission fee. The same situation occurs in the manufacturer's and the platform's profits. When the initial carbon emission level is relatively high, the manufacturer's profit increases with θ. However, when the emission level is relatively low, the manufacturer's profit first decreases and then increases with θ. When it comes to the platform's profit, if the initial carbon emission level is in the middle range, the platform makes more profit as consumer's acceptance increases. If the emission level is too low or too high, the platform's profit exhibits a first increasing then decreasing and finally increasing tendency as θ increases.

It can be derived from Lemma 3(2) that, the carbon abatement level, the retail price and the platform's profits show analogous change tendency with the consumer's environmental sensitivity. When the initial carbon emission is high, these three equilibrium results all decrease with η. But when the initial carbon emission is low, these three results increase with the consumer's environmental sensitivity if η is moderate, if η is too low or too high, they decrease with η. Besides, the manufacturer's profit shows relatively simple change tendency, that is, it first increases and then decreases as the consumer's environmental sensitivity increases. These results reflect that, when the manufacturer makes the decision of investing in green technology to achieve carbon abatement, he would consider the initial carbon emission level, consumer's acceptance and consumer's environmental sensitivity.

Next, we resort to numerical analyses to verify the observations in Lemma 3. Figure 4 presents the changes of equilibrium results in Scenario AT with respect to parameters θ and η. Figure 4A shows that the price and



(a) (b)

FIGURE 4. Variations in the equilibrium results in Scenario AT with respect to θ and η: $e_0 = 1$, $\gamma = 0.1$. (A) $\eta = 0.1, \alpha = 0.2$. (B) $\theta = 0.2, \alpha = 0.2$.

carbon abatement level both increase with θ. When consumer's acceptance of products becomes higher, the manufacturer's incentive to reduce carbon emission becomes weaker because he no longer needs to obtain the consumer's demand through environmental action. Both the manufacturer's and the platform's profits increase sharply when θ is larger than a threshold in Scenario AT than in Scenario RT. This is because in Scenario A, the manufacturer controls the pricing power of the final products and he could charger higher retail price when investing more in green technology. From Figure 4B, it can be observed that the retail price and carbon abatement level show analogous tendencies with them in Mode RT. What's more, the change tendencies of supply chain member's profits are also analogous with them in Mode RT.

4.2.3. Mode AB: with green investment and blockchain adoption

In this mode, the manufacturer invests in green technology to carry out carbon abatement at a level of e_{AB} with a cost of $\frac{1}{2}{e_{\mathrm{AB}}}^2$. Then the platform deploys blockchain technology to disclose environmental information I_{AB} with a cost of $\frac{1}{2}{I_{\mathrm{AB}}}^2$. Then, as in the base mode AN, the manufacturer decides the retail price p_{AB}.

The manufacturer's and platform's profit functions are shown below:

$$\pi_{\mathrm{M}}^{\mathrm{AB}} = (1-\gamma)\cdot p \cdot d_{\mathrm{B}} - \frac{1}{2}e^2 = (1-\gamma)\cdot p_{\mathrm{AB}} \cdot [1-\eta\cdot(e_0 - e_{\mathrm{AB}}) + \alpha \cdot I - p_{\mathrm{AB}}] - \frac{1}{2}{e_{\mathrm{AB}}}^2,$$
$$\pi_{\mathrm{P}}^{\mathrm{AB}} = \gamma \cdot p \cdot d_{\mathrm{B}} - \frac{1}{2}I^2 = \gamma \cdot p_{\mathrm{AB}} \cdot [1-\eta\cdot(e_0 - e_{\mathrm{AB}}) + \alpha \cdot I - p_{\mathrm{AB}}] - \frac{1}{2}{I_{\mathrm{AB}}}^2.$$

This paper derives the equilibrium results as follows in Proposition 4.

Proposition 4. *When satisfying* $(\alpha^2\gamma - 2)^2 - 2\eta^2(1-\gamma) > 0$*, the equilibrium results in Mode AB are*

$$e_{\mathrm{AB}}^* = \frac{2\eta(1-\gamma)\cdot(1-\eta\cdot e_0)}{(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma)},$$
$$I_{\mathrm{AB}}^* = \frac{\alpha\gamma(\alpha^2\gamma-2)\cdot(\eta\cdot e_0 - 1)}{(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma)},$$
$$p_{\mathrm{AB}}^* = \frac{(\alpha^2\gamma-2)\cdot(\eta\cdot e_0 - 1)}{(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma)}.$$

The manufacturer's and the platform's equilibrium profits are:

$$\pi_{\mathrm{M}}^{\mathrm{AB}*} = \frac{(1-\gamma)\cdot(\eta\cdot e_0 - 1)^2}{(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma)},$$

$$\pi_{\mathrm{P}}^{\mathrm{AB}*}=\frac{-\gamma\left(\alpha^2\gamma-2\right)^3\cdot\left(\eta\cdot e_0-1\right)^2}{2\left[\left(\alpha^2\gamma-2\right)^2-2\eta^2(1-\gamma)\right]^2}.$$

In order to explore how the equilibrium results are impacted by the parameters: consumer's environmental sensitivity and consumer's preference for the environmental information, this paper uses sensitive analyses to show the results in Lemma 4.

Lemma 4. *The following are sensitive analyses of the decision variables in Mode RB with respect to consumer's environmental sensitivity* (η) *and consumer's preference for the environmental information* (α)*:*

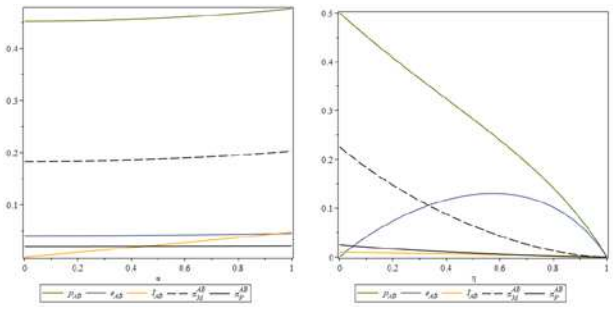
(1) *When* $0\le\eta\le\frac{(2-\alpha^2\gamma)[e_0(2-\alpha^2\gamma)+\sqrt{{e_0}^2(2-\alpha^2\gamma)^2+2(\gamma-1)}]}{2(1-\gamma)}$, $\frac{\partial e_{\mathrm{AB}}^*}{\partial\eta}\le 0$, *otherwise* $\frac{\partial e_{\mathrm{AB}}^*}{\partial\eta}>0$. *When* $e_0\le\frac{\sqrt{2(1-\gamma)}}{\alpha^2\gamma-2}$, $\frac{\partial p_{\mathrm{AB}}^*}{\partial\eta}\ge 0$, $\frac{\partial I_{\mathrm{AB}}^*}{\partial\eta}\ge 0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial\eta}\ge 0$; *when* $e_0>\frac{4(1-\gamma)}{(\alpha^2\gamma-2)^2+2(1-\gamma)}$, $\frac{\partial p_{\mathrm{AB}}^*}{\partial\eta}\ge 0$, $\frac{\partial I_{\mathrm{AB}}^*}{\partial\eta}\ge 0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial\eta}\ge 0$ *if* $\frac{2(1-\gamma)-\sqrt{2\alpha^2\gamma^2{e_0}^2[\alpha^2(\gamma-1)-4]+8\gamma{e_0}^2(\alpha^2+1)+4[(\gamma-1)^2-2{e_0}^2]}}{2e_0(1-\gamma)}\le\eta\le\frac{2(1-\gamma)+\sqrt{2\alpha^2\gamma^2{e_0}^2[\alpha^2(\gamma-1)-4]+8\gamma{e_0}^2(\alpha^2+1)+4[(\gamma-1)^2-2{e_0}^2]}}{2e_0(1-\gamma)}$, *otherwise* $\frac{\partial p_{\mathrm{AB}}^*}{\partial\eta}<0$, $\frac{\partial I_{\mathrm{AB}}^*}{\partial\eta}<0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial\eta}<0$; *when* $\frac{\sqrt{2(1-\gamma)}}{\alpha^2\gamma-2}<e_0<\frac{4(1-\gamma)}{(\alpha^2\gamma-2)^2+2(1-\gamma)}$, $\frac{\partial p_{\mathrm{AB}}^*}{\partial\eta}>0$, $\frac{\partial I_{\mathrm{AB}}^*}{\partial\eta}>0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial\eta}>0$ *if* $\eta\le\frac{2(1-\gamma)-\sqrt{2\alpha^2\gamma^2{e_0}^2[\alpha^2(\gamma-1)-4]+8\gamma{e_0}^2(\alpha^2+1)+4[(\gamma-1)^2-2{e_0}^2]}}{2e_0(1-\gamma)}$, *otherwise* $\frac{\partial p_{\mathrm{AB}}^*}{\partial\eta}<0$, $\frac{\partial I_{\mathrm{AB}}^*}{\partial\eta}<0$ *and* $\frac{\pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial\eta}<0$. *When* $e_0\ge\frac{2\eta(1-\gamma)}{(\alpha^2\gamma-2)^2}$, $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{AB}*}}{\partial\eta}\le 0$; *otherwise,* $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{AB}*}}{\partial\eta}>0$.

(2) $\frac{\partial e_{\mathrm{AB}}^*}{\partial\alpha}>0$, $\frac{\partial I_{\mathrm{AB}}^*}{\partial\alpha}>0$, $\frac{\partial p_{\mathrm{AB}}^*}{\partial\alpha}>0$, $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{AB}*}}{\partial\alpha}>0$, $\frac{\partial\pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial\alpha}>0$.

Lemma 4(1) reflects that, the carbon abatement level shifts with the changes in η first decreasing and then increasing. This indicates that the manufacturer's incentive to invest in green technology displays a non-monotonic tendency with consumer's environmental sensitivity. The consumer's high sensitivity on the product's environmentally friendly property would harm the manufacturer's incentive to reduce the product's carbon emission. The platform's retail price, information disclosure level and profit present identical changes with η and the changes depending on the initial carbon emission level. When e_0 is low, they all increase with η. But when e_0 is large, they first decrease and then increase and finally decrease with η. Thus, the platform makes decisions on information disclosure level considering not only the consumer's sensitivity but also the initial carbon emission level. Moreover, the manufacturer's profit changes in η also affected by the initial carbon emission level. When e_0 is small, the manufacturer's profit monotonically decreases in η. However, when e_0 is large, the manufacturer's profit presents contrary tendency.

From Lemma 4(2), this paper observes that all the equilibrium results present a monotonically increasing tendency with the consumer's preference for the environmental information. This hinges on the rationale that when consumers prefer more environmental information, the manufacturer would have more motivation to invest in green technology, thus the carbon abatement level increases. Correspondingly, the platform intends to disclosure more related information to the consumers so as to attract more consumer's purchase. Because the manufacturer and the platform invest in carbon abatement and blockchain technology, respectively, the manufacturer charges higher price to cover their cost. What's more, their decisions stimulate the consumer demand which bring them more profits as a result.

We use numerical analyses to visually demonstrate the findings in Lemma 4. Figure 5A shows that, the manufacturer's profit is much higher than in Scenario RB which hinges on the manufacturer's pricing power which endows him the right to charge higher retail price without the participation of the platform. Figure 5B indicates that, the descent of manufacturer's profit is more drastic than the platform's. This comes the rationale that as the consumers are more and more sensitive about the carbon emission, the manufacturer's action of reducing investment in carbon emission brings increasingly serious negative impacts on his profits. But the platform only charges a proportion of the manufacturer's profit which weakens the harmful impact on profit.



(a) (b)

FIGURE 5. Variations in the equilibrium results in Scenario AB with respect to α and η: $e_0 = 1$, $\gamma = 0.1$. (A) $\eta = 0.1$ and $\theta = 0.2$. (B) $\theta = 0.2$ and $\alpha = 0.2$.

5. COMPARISONS

In this section, this paper first investigates how does the manufacturer make decisions of whether to invest in green technology to reduce carbon emission indifferent scenarios. This paper then discusses whether the platform would intend to adopt blockchain technology to disclose the carbon abatement information to consumers at an adoption cost. Finally, this paper summarizes the optimal decision combination which is preferred by all the supply chain members.

5.1. The investment in green technology

This paper explores in this subsection to analyze the manufacturer's decision of whether to invest in green technology. Through the green investment, the manufacturer could reduce the carbon emission which is beneficial for the environmental sustainability. In the model setting, the carbon abatement could improve the consumer's utility who are environmentally sensitive. And the manufacturer could expand market demand of his products. this paper compares the manufacturer's profits in different modes in the two scenarios to verify his optimal decisions.

This paper first compares the manufacturer's profits in Modes RN, RT and RB, to obtain his optimal decision in Scenario R. The results are shown in Proposition 5.

Proposition 5. *In Scenario R, there exists two consumer's acceptance thresholds* θ_1^* *and* θ_2^* $(0 < \theta_1^* < \theta_2^* < 1)$*, such that:*

(1) *When* $0 < \theta < \theta_1^*$*, there is* $\pi_{\mathrm{M}}^{\mathrm{RT}^*} > \pi_{\mathrm{M}}^{\mathrm{RN}^*} > \pi_{\mathrm{M}}^{\mathrm{RB}^*}$*, the manufacturer prefers Mode RT;*
(2) *When* $\theta_1^* < \theta < \theta_2^*$*, there is* $\pi_{\mathrm{M}}^{\mathrm{RT}^*} > \pi_{\mathrm{M}}^{\mathrm{RB}^*} > \pi_{\mathrm{M}}^{\mathrm{RN}^*}$*, the manufacturer prefers Mode RT;*
(3) *When* $\theta_2^* < \theta < 1$*, there is* $\pi_{\mathrm{M}}^{\mathrm{RB}^*} > \pi_{\mathrm{M}}^{\mathrm{RT}^*} > \pi_{\mathrm{M}}^{\mathrm{RN}^*}$*, the manufacturer prefers Mode RB.*

This paper derives from Proposition 5 that, in Scenario R, the manufacturer would always prefer to invest in green technology to reduce the carbon emission level rather than not invest. It is obviously that, investment in green technology can reduce the carbon emission level effectively which brings positive effects in the consumer's utility. Thus, the consumers will make more purchase and expand the manufacturer's product demand. What's more, when consumer's acceptance of product is low, the manufacturer always intends the platform not deploy blockchain technology. This is rational because when consumers have low preference for the product, no matter whether the manufacturer and the platform making efforts to promote the product's environmentally friendly property, they would not purchase more products. Thus, although the manufacturer would make investment to reduce the carbon emission to improve the products' environmentally friendly property, he would not want the platform to make more additional efforts which may bring extra costs. However, when consumers have high

preference for the manufacturer's products, he would not only make investment to raise the consumer's utility, but also hope the platform also play a more effective role. Thus, the manufacturer prefers to invest in green technology by himself and the platform deploy to adopt blockchain technology in this situation. German energy company Naturstrom collaborated with Lition to launch a blockchain based platform in the energy market, enabling consumers to purchase electricity derived from renewable energy sources[5]. The platform leverages blockchain technology to trace the origin and usage of energy, while utilizing smart contracts to ensure the authenticity of the renewable energy supply. Consumers can access the mobile application to view the carbon footprint and type of electricity they have purchased.

This paper then makes comparison of the manufacturer's profits in Modes AN, AT and AB, to obtain whether he would invest in green technology in Scenario A. This paper obtains the results and show them in the following proposition.

Proposition 6. *In Scenario A, there exists two consumer's acceptance thresholds* θ_3^* *and* θ_4^* $(0 < \theta_3^* < \theta_4^* < 1)$, *such that:*

(1) *When* $0 < \theta < \theta_3^*$, $\pi_M^{AT^*} > \pi_M^{AN^*} > \pi_M^{AB^*}$, *the manufacturer prefers Mode AT;*
(2) *When* $\theta_3^* < \theta < \theta_4^*$, $\pi_M^{AT^*} > \pi_M^{AB^*} > \pi_M^{AN^*}$, *the manufacturer prefers Mode AT;*
(3) *When* $\theta_4^* < \theta < 1$, $\pi_M^{AB^*} > \pi_M^{AT^*} > \pi_M^{AN^*}$, *the manufacturer prefers Mode AB.*

Proposition 6 shows analogous results as Proposition 5. When consumer's acceptance of products is low and moderate, the manufacturer's optimal decision comes into invest in green technology. As explained before, when consumers show low acceptance for products, the manufacturer investing in green technology could achieve some goals, such as, establishing environmentally friendly brand image, attracting more environmental sensitive consumers, enlarging brand influence in the society. Besides, when θ is extremely low, the manufacturer wishes the platform not to adopt blockchain technology. This is because the platform could completely improve the consumers' acceptance through blockchain technology, which will damage the manufacturer's profits. When consumer's acceptance lies in the middle range, the manufacturer's preference changes from investing in carbon abatement to hoping the platform deploy blockchain technology and to taking no action. The rationale behind this result lies in the same reason as described before. What's more, in this scenario, agency selling format is adopted in the supply chain, the manufacturer controls the pricing power of the final products and only pays a proportion of commission fee for the platform. Therefore, he may wish the platform do not apply blockchain technology to disclosure information, which would bring prohibitive cost and do harm for his total profit. When the consumers very prefer the manufacture's products, the manufacturer would like the platform to deploy blockchain technology rather than not. Because in this situation, he wants the platform to make efforts to raise consumer's preference for the products together with him. Through this way, the supply chain members in the upstream and downstream can play a synergistic role which will bring more consumer demand to the largest extent and result in more profits for not only the manufacturer but also the platform.

We resort to numerical study to analyze the joint impacts of consumer's acceptance of products (θ) and consumer's environmental sensitivity (η) on the manufacturer's mode choices. We suppose that $e_0 = 1$, $\alpha = 0.2$, $\gamma = 0.1$.

It can be discovered that the optimal decisions of the manufacturer and the platform are slightly different under different scenarios. Figure 6A shows that, line 1 divides the area into two regions: in the left side of line 1, the manufacturer prefers Mode RN but he prefers Mode RB in the right side of line 1. This result indicates that, as η increases, the manufacturer's preference changes from deploying blockchain technology to not; while as θ increases, his preference is opposite. The increase of consumer's acceptance of product induces the manufacturer to incline to the platform's information disclosure action. This comes from the reason that the adoption of blockchain technology could dispel consumers' concern of product's environmental property which significantly raises the consumes' utility. Figure 6A also demonstrates that, line 2 divides the area into to two regions, the right side of line 2 represents that the manufacturer prefers Mode RB, while in the left side the manufacturer prefers

[5] https://www.lition.io/about.php.

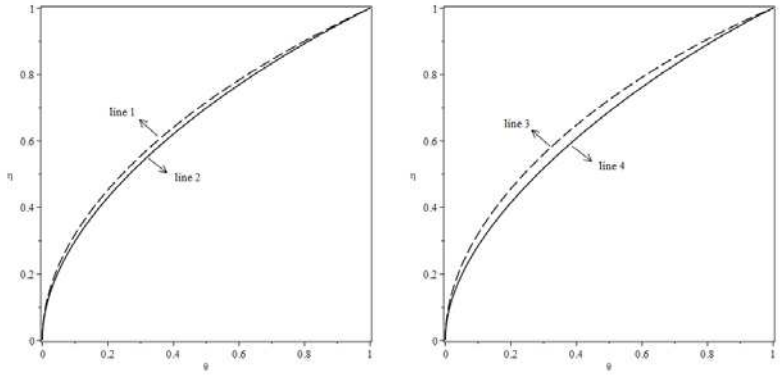


FIGURE 6. Mode preference for the manufacturer: $e_0 = 1$, $\alpha = 0.2$, $\gamma = 0.1$. (A) Scenario R. (B) Scenario A.

Mode RT. As consumers are more and more sensitive about the product's carbon emission, the manufacturer prefers the platform not to deploy blockchain technology. The rationale behind this result hinges on that, the adoption of blockchain is costly and results in an increase in the manufacturer's cost which hurts his profitability. It can be inferred that, when consumers are highly sensitive about the product's carbon emission, the reduction of carbon emission contributes more than information disclosure. Thus, manufacturers usually intend to take actions by themselves to reduce carbon emission other than resorting to platforms' adoption of blockchain technology. From the comparison of Figures 4A and 4B, the manufacturer's mode choices are analogous in Scenarios R and A.

5.2. The adoption of blockchain technology

In this subsection, this paper analyzes whether the platform incline to adopt blockchain technology to disclose the information about environmentally friendly products. this paper compares the equilibrium results in Scenarios R and A, respectively, to identify the platform's initiative.

First, this paper compares the platform's profits in Modes RN, RT and RB, to obtain the platform's optimal decision of whether to deploy blockchain technology.

Proposition 7. *In Scenario R, there exists two consumer's acceptance thresholds* θ_5^* *and* θ_6^* $(0 < \theta_1^* < \theta_2^* < 1)$, *such that:*

(1) *When* $0 < \theta < \theta_5^*$, *there is* $\pi_{\mathrm{P}}^{\mathrm{RT}^*} > \pi_{\mathrm{P}}^{\mathrm{RN}^*} > \pi_{\mathrm{P}}^{\mathrm{RB}^*}$, *the platform prefers Mode RT;*
(2) *When* $\theta_5^* < \theta < \theta_6^*$, *there is* $\pi_{\mathrm{P}}^{\mathrm{RT}^*} > \pi_{\mathrm{P}}^{\mathrm{RB}^*} > \pi_{PM}^{\mathrm{RN}^*}$, *the platform prefers Mode RT;*
(3) *When* $\theta_6^* < \theta < 1$, *there is* $\pi_{\mathrm{P}}^{\mathrm{RB}^*} > \pi_{\mathrm{P}}^{\mathrm{RT}^*} > \pi_{\mathrm{P}}^{\mathrm{RN}^*}$, *the platform prefers Mode RB.*

This paper observes from Proposition 7 that, the platform's optimal decisions are always analogous with the manufacturer decisions in Scenario R. When the consumer's acceptance of products is relatively low, the platform would prefer not to adopt blockchain technology to disclosure carbon abatement information rather than adopt blockchain technology. As is well-known, the deployment of blockchain technology is costly and prohibitive. In this situation, the consumer's purchase desire is extremely low, even though the platform make efforts to disclosure information to the consumer, it makes very little difference. Besides, in this scenario, reselling format is applying in the supply chain, the platform controls the final pricing power of the products, she would be more likely not to adopt blockchain technology when consumer's acceptance is low. This result comes from the reason that the platform is always risk averse, she intends to avoid the market risk from the low

consumer demand. Thus, she would not to adopt costly blockchain technology in this situation. However, when the consumers exhibit discernible preference for the products, which means that efforts of the manufacturer and the platform will bring obvious growth of the consumer demandant information to consumers. Carrefour has developed the Food Trust platform in collaboration with IBM[6]. Thus, in this situation, the platform would like to adopt blockchain technology to disclose environmentally friendly information to consumers so as to benefit from the demand growth. Global retail giant Carrefour collaborates with its suppliers to trace the supply chain of poultry products using blockchain technology, and disclose relevant records about the information of each chicken from hatching to slaughtering on the blockchain[7]. Consumers can obtain information about the origin, food safety, and other details of the product by scanning the QR code on the product packaging.

This paper then compares the platform's profits in Modes AN, AT and AB, to verify whether the platform would like to deploy blockchain technology.

Proposition 8. *In Scenario A, there exists a consumer's acceptance thresholds* θ_7^* $(0 < \theta_7^* < 1)$, *such that:*

(1) *When* $0 < \theta < \theta_7^*$, *there is* $\pi_{\mathrm{P}}^{\mathrm{AT}^*} > \pi_{\mathrm{P}}^{\mathrm{AN}^*} > \pi_{\mathrm{P}}^{\mathrm{AB}^*}$, *the platform prefers Mode AT;*
(2) *When* $\theta_4^* < \theta < 1$, *there is* $\pi_{\mathrm{P}}^{\mathrm{AB}^*} > \pi_{\mathrm{P}}^{\mathrm{AT}^*} > \pi_{\mathrm{P}}^{\mathrm{AN}^*}$, *the platform prefers Mode AB.*

From Proposition 8, this paper derives that when consumer's acceptance of products is lower than a certain threshold, the platform prefers not to adopt blockchain technology but hope the manufacturer to reduce carbon emission through investment in green technology. As the consumer's acceptance of products increases, the platform's optimal decision changes, she would like to adopt blockchain technology than not. And she prefers the manufacturer to invest in green technology to reduce carbon emission. In agency selling format, the platform charges a proportion of the manufacturer's profit, so she always prefers the manufacturer to improve carbon abatement level which can bring more consumer demand and benefits the platform's total profits. Besides, when consumer's acceptance of products is very high, the platform has more incentive to adopt blockchain technology to disclose carbon abatement information which can bring more demand from the environmental consumer and result in more profit for the platform.

Figure 7 shows the platform's mode choices in Scenarios R and A. The platform presents analogous preferences with the manufacturer considering the impacts of consumer's acceptance of product and consumer's environmental sensitivity. A slight difference exists that the impacts of the two parameters (*i.e.*, θ and η) are obvious for the platform's optimal options than the manufacturer's. As shown on the figures, the two lines are further apart in Figure 5 than in Figure 4. The intuition behind this result lies in the fact that, the platform's decision of adopting blockchain technology to disclose information directly influences the consumer's acceptance of products. The blockchain adoption significantly improves the consumer's acceptance which brings an obvious increase of the consumer's utility.

5.3. Discussion

In this study, this paper has investigated the manufacturer's decision of developing green technology and the platform's decision of adopting blockchain technology in Scenarios R and A. The insights obtained from the analyses provide some guidance to manufacturers, platforms in related supply chain and policymakers. For manufacturers, they have two incentives to develop green technology. On the one hand, green technology can reduce the carbon emission of the products. The consumers in the market are environmental sensitive, they prefer the products with lower carbon emission level. Thus, manufacturers carbon abatement action would satisfy the consumers desire which attracts more environmental sensitive consumers. On the other hand, if the manufacturer reduces carbon emission, the platforms have the incentive to disclose the environmental information to consumers, which is beneficial for the manufacturers' brand image, and enlarge their brand influence in the society. From the above two reasons, this paper finds that the manufacturers' investment in

[6] https://www.carrefour.com/en/news/food-traceability-carrefour-blockchain-pioneer-europe-has-joined-ibm-food-trust-platform-take.

[7] https://www.carrefour.com/sites/default/files/2019-12/carrefour_press_release_81018_eng.pdf.

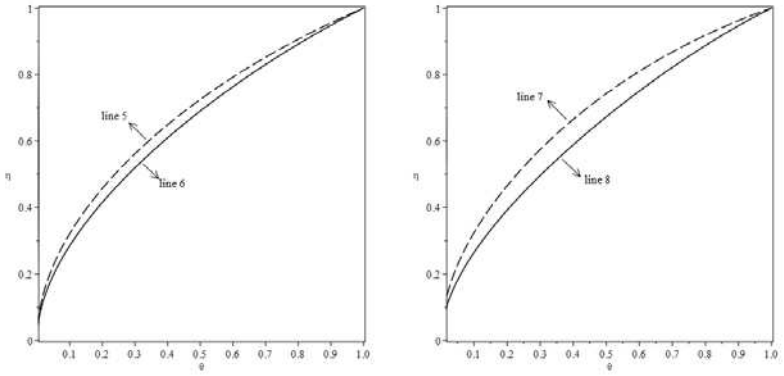


FIGURE 7. Mode preference for the platform: $e_0 = 1$, $\alpha = 0.2$, $\gamma = 0.1$. (A) Scenario R. (B) Scenario A.

carbon abatement could help them establish a wider customer base and gain more marketing opportunities. Interface, a globally leading commercial carpet manufacturer, is committed to reducing carbon emissions and environmental impact[8]. They have invested in green technologies and innovated a closed-loop manufacturing model to minimize resource consumption and carbon emissions through the green, high-efficiency reclamation and reuse of discarded carpets[9]. Additionally, they continuously enhance their level of green technologies by utilizing renewable materials and improving production processes to reduce environmental impact[10]. These environmental initiatives not only gain recognition and support from environmentally conscious consumers but also provide the company with a competitive edge and sustainable profit growth. This paper finds that the platforms usually prefer to sell products with lower carbon emissions, such as JD.com, Amazon. They usually prefer the manufacturers to take actions to reduce carbon emission. Besides, in promoting green consumption initiatives, it is evident that e-commerce retail platforms can play a more proactive role. Thus, the platforms have the incentive to adopt blockchain technology to disclose the product's carbon abatement level to consumers which not only attracts more consumption but is beneficial for the manufacturers to enhance their total profits. According to a report released by NYU Stern School of Business in 2021[11], products marketed with sustainability as a selling point contributed to over half (54.7%) of the growth in the packaged consumer goods market from 2015 to 2019. The growth rate of these sustainability-focused products exceeded that of non-sustainable products by more than seven times.

6. Conclusions and insights

This paper examines a supply chain in which an upstream manufacturer sells products to consumers through a downstream retail platform. The manufacturer and platform cooperate under either a reselling or agency selling model, depending on who controls the pricing power. The manufacturer's production process generates carbon emissions for each product sold, and given that consumers are environmentally conscious, the manufacturer faces the decision of whether to invest in green technology to reduce these emissions. However, consumers

[8] https://www.interface.com.cn/collections/carbon-negative.

[9] https://www.interface.com/US/en-US/sustainability/sustainability-overview.html.

[10] https://www.interface.com/US/en-US/more-from-interface/press-room/interface-commits-to-absolute-emission-reduction-efforts.html.

[11] https://www.stern.nyu.edu/experience-stern/about/departments-centers-initiatives/centers-of-research/center-sustainable-business/research/csb-sustainable-market-share-index.

are unaware of the manufacturer's actions and perceive a discount on products sold through the platform's retail channel. As a result, the platform has an incentive to disclose relevant information to consumers *via* blockchain technology. On the one hand, blockchain technology can significantly increase consumer acceptance of the products sold through the platform. On the other hand, consumer utility improves in proportion to the level of product traceability enabled by blockchain. However, both carbon abatement and blockchain adoption incur costs for the manufacturer and the platform, respectively. This paper defines two scenarios based on the supply chain's selling format, each containing three distinct modes: (1) no green investment and no blockchain adoption (Modes RN and AN), (2) green investment without blockchain (Modes RT and AT), and (3) green investment with blockchain adoption (Modes RB and AB).

By investigating the optimal decisions of the manufacturer's decision in green investment and the platform decision on blockchain technology, we have obtained the following findings. This paper finds that, the manufacturer and the platform display different attitude towards the actions to boost the market. The manufacturer always have an incentive to invest in green technology rather than taking no action in both scenarios. However, the platform's decision on blockchain adoption depends on the consumer's acceptance of products. The results also show that the consumer's acceptance of products (θ) and environmental sensitivity (η) play decisive roles in the manufacturer's and platform's decisions. Specifically, the manufacturer's and platform's mode choices are always analogous and are mainly impacted by the consumer's acceptance of product (θ). When the consumer's acceptance of products is low and moderate, both the manufacturer and the platform prefer Modes RT and AT, that is, they both expect to develop green technology to reduce carbon emission and not adopt blockchain technology to disclose information in the supply chain. However, when the consumer's acceptance of products is high, Modes RB and AB are preferred by them. What's more, the consumer's acceptance of products (θ) and environmental sensitivity (η) play opposite roles in the supply chain member's mode choices. As the increase of consumer's acceptance of products, the manufacturer's and the platform's choices both change from Mode RN/RT (Mode AN/AT) to Mode RB (Mode AB). The increase of the consumer's environmental sensitivity leads the supply chain members' mode choices change opposite, that is, from Mode RB (Mode AB) to Mode RN/RT (Mode AN/AT). That is, they are both less likely to take actions, including reducing carbon emission and disclosing information. Furthermore, they always prefer Mode RT (Mode AT) than Mode RN (Mode AN) which indicates that, the supply chain members always prefer the manufacturer to invest in green technology rather than taking no action. Besides, sensitive analyses show that, the consumer's acceptance for product and preference for the environmental information play analogous roles for the supply chain members' decision variables and profits, they all increase with θ and α. But the consumer's environmental sensitivity (η) plays different roles in the decision variables.

Based on the analyses, we have gleaned several managerial insights that are beneficial not only for the sustainable management of supply chain members but also for government and regulatory bodies. Firstly, this paper offers guidance to manufacturers on the decision to invest in green technology for carbon abatement. Generally, a manufacturer would opt to invest in green technology to reduce carbon emissions, regardless of the level of consumer acceptance or environmental sensitivity. However, consumer acceptance of products significantly influences the manufacturer's preference for platform actions. When acceptance is low to moderate, manufacturers prefer that platforms do not implement blockchain technology due to its substantial costs. Conversely, when consumer acceptance is high, manufacturers favor platforms disclosing related environmental information to consumers, even if the adoption cost is prohibitive. These findings indicate that manufacturers are incentivized to reduce carbon emissions through their own technological innovations and also wish for platforms to disclose environmental information to consumers. Such disclosures can help manufacturers cultivate an environmentally friendly image, attracting more consumers who are concerned about carbon emissions. To encourage this, manufacturers should consider sharing the costs of blockchain technology with platforms, collaborating on blockchain development, and increasing the commission fees shared with platforms. The study also suggests that consumer acceptance of products plays a decisive role in the platform's optimal decision-making. Platforms are more likely to adopt blockchain technology to disclose information when consumer acceptance is high. In contrast, when acceptance is low to moderate, platforms prefer that manufacturers focus on reducing carbon emissions.

Although information disclosure is beneficial, the high cost of blockchain adoption can be a deterrent. Therefore, platforms might seek cooperation with manufacturers to achieve a mutually beneficial outcome. Furthermore, the paper finds that the selling format in the supply chain does not significantly influence decisions, but it does interact with consumer acceptance to slightly affect the decisions of manufacturers and platforms. When an agency selling format is used, profit fluctuations among supply chain members can be more dramatic than with a reselling format. Finally, this work proposes several meaningful suggestions for governments. Authorities should design policies to support manufacturers' technological innovations aimed at greater carbon emission reductions. Additionally, governments should provide fiscal subsidies to platforms to encourage the adoption of blockchain technology, which, despite its high cost, is beneficial for supply chain operations and societal development. In conclusion, this paper put forward academical and practical advice for the supply chain member's. Manufacturers should invest in green technologies and collaborate with platforms to share the benefits of environmental disclosures. Platforms should assess consumer acceptance when deciding on blockchain adoption for supply chain transparency. Governments can play a pivotal role by providing fiscal incentives and subsidies to foster a sustainable supply chain ecosystem. Both academic and practical explorations should continue to evaluate the integration of blockchain technology in various sectors to understand its broader implications on supply chain management and societal benefits.

The present study acknowledges certain limitations that suggest avenues for future inquiry into the realms of carbon abatement and the application of blockchain technology within supply chain management. Initially, the analysis does not incorporate the impact of compulsory governmental policies on carbon emissions, such as domestic carbon taxes or the carbon border adjustment mechanism applicable to international trade. Furthermore, the research posits that the incentive to adopt blockchain technology resides solely with the platform operators. However, it is essential to recognize that market manufacturers, including entities like IKEA, Tesla, and Interface, also possess motivations to innovate with blockchain technology to enhance the dissemination of carbon emission data throughout their production processes to end consumers. Moreover, there is a subset of manufacturers who are inclined to collaborate with platforms to establish blockchain infrastructure, thereby ensuring greater transparency of their carbon emissions from the upstream production phase to the downstream retail sector. Consequently, subsequent research endeavors could beneficially integrate the incentives of manufacturers into the analysis.

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References

[1] V. Abhishek, J.M. Swaminathan and J. Zhang, Strategic sourcing and quality competition: Do wholesalers build sustainable supply chains? *Manage. Sci.* **62** (2016) 642–661.

[2] S.S. Ali, H. Barman, R. Kaur, H. Tomaskova and S.K. Roy, Multi-product multi echelon measurements of perishable supply chain: fuzzy non-linear programming approach. *Mathematics* **9** (2021) 2093.

[3] A. Babaei, E.B. Tirkolaee and S.S. Ali, Innovative supply chain network design with two-step authentication and environmentally-friendly blockchain technology. *Ann. Oper. Res.* (2024) 1–31.

[4] V. Babich and G. Hilary, Distributed ledgers and operations: What operations management researchers should know about blockchain technology. *Manuf. Serv. Oper. Manage.* **22** (2020) 223–240.

[5] C. Bai and J. Sarkis, A supply chain transparency and sustainability technology appraisal model for blockchain technology. *Int. J. Prod. Res.* **58** (2020) 2142–2162.

[6] H. Barman, M. Pervin and S.K. Roy, Impacts of green and preservation technology investments on a sustainable EPQ model during COVID-19 pandemic. *RAIRO-Oper. Res.* **56** (2022) 2245–2275.

[7] H. Barman, M. Pervin, S.K. Roy and G.W. Weber, Analysis of a dual-channel green supply chain game-theoretical model under carbon policy. *Int. J. Syst. Sci. Oper. Logistics* **10** (2023) 2242770.

[8] H. Barman, S.K. Roy, L. Sakalauskas and G.W. Weber, Inventory model involving reworking of faulty products with three carbon policies under neutrosophic environment. *Adv. Eng. Inf.* **57** (2023) 102081.

[9] S. Bhunia, S.K. Das, J. Jablonsky and S.K. Roy, Evaluating carbon cap and trade policy effects on a multi-period bi-objective closed-loop supply chain in retail management under mixed uncertainty: towards greener horizons. *Expert Syst. App.* **250** (2024) 123889.

[10] T. Chen, Y. Li and L. Qiu, Online agency selling versus reselling: a model of competition with information updating. *Marketing Sci.* **36** (2017) 864–885.

[11] Y. Cheng and X. Yao, Carbon intensity reduction assessment of renewable energy technology innovation in China: a panel data model with cross-section dependence and slope heterogeneity. *Renew. Sustain. Energetic Rev.* **135** (2021) 110157.

[12] T.M. Choi, Blockchain-technology-supported platforms for diamond authentication and certification in luxury supply chains. *Transp. Res. Part E: Logistics Transp. Rev.* **128** (2019) 17–29.

[13] T.M. Choi, L. Feng and R. Li, Information disclosure structure in supply chains with rental service platforms in the blockchain technology era. *Int. J. Prod. Econ.* **221** (2020) 107473.

[14] K. Christidis and M. Devetsikiotis, Blockchains and smart contracts for the internet of things. *IEEE Access* **4** (2016) 2292–2303.

[15] G.L. Clark, A. Feiner and M. Viehs, From the stockholder to the stakeholder: How sustainability can drive financial outperformance. *J. Environ. Investing* **6** (2015) 138–147.

[16] R.G. Eccles, I. Ioannou and G. Serafeim, The impact of corporate sustainability on organizational processes and performance. *Manage. Sci.* **60** (2014) 2835–2857.

[17] O. Gaffney and W. Steffen, The anthropocene equation. *Anthropocene Rev.* **4** (2017) 53–61.

[18] A. Goli, D. Bozanic, F. Zhou and I. Ali, The role of blockchain technology toward a sustainable energy future. *Front. Energy Res.* **12** (2024) 1361080.

[19] A. Hamidoğlu and G.W. Weber, A novel Nash-based low-carbon implementation in agricultural supply chain management. *J. Clean. Prod.* **449** (2024) 141846.

[20] O. Hawn and I. Ioannou, Mind the gap: the interplay between external and internal actions in the case of corporate social responsibility. *Strategic Manage. J.* **39** (2018) 3039–3068.

[21] B. Horvath and T. Krick, The sustainable investment landscape: a survey of the definitions, organizations and investment strategies that comprise sustainable investing. *J. Clean. Prod.* **162** (2017) 20–28.

[22] Y. Huang, C. Wei, Y. Sun and Z. He, Coordination in a two-echelon supply chain with reselling, trade-in, and agency selling. *Eur. J. Oper. Res.* **286** (2020) 13–26.

[23] J. Huang, B. Xu and X. Yan, Selling mode choice and blockchain adoption in an e-commerce platform with information disclosure. *Electron. Commer. Res. App.* **62** (2023) 101331.

[24] M. Iansiti and K.R. Lakhani, The truth about blockchain. *Harvard Bus. Rev.* **95** (2017) 119–127.

[25] P. Jia, K. Li and S. Shao, Choice of technological change for China's low-carbon development: evidence from three urban agglomerations. *J. Environ. Manage.* **206** (2018) 1308–1319.

[26] M. Kouhizadeh, S. Saberi and J. Sarkis, Blockchain technology and the sustainable supply chain: theoretically exploring adoption barriers. *Int. J. Prod. Econ.* **231** (2021) 107831.

[27] Z. Li, X. Xu, Q. Bai, X. Guan and K. Zeng, The interplay between blockchain adoption and channel selection in combating counterfeits. *Transp. Res. Part E: Logistics Transp. Rev.* **155** (2021) 102451.

[28] J. Li, X. Liu and X. Shao, Collaborative carbon emission reduction in power supply and demand entities based on blockchain technology. *Int. J. Electr. Power Energy Syst.* **157** (2024) 109840.

[29] B. Lin and J. Zhu, Determinants of renewable energy technological innovation in China under CO_2 emissions constraint. *J. Environ. Manage.* **247** (2019) 662–671.

[30] Y. Liu, D. Ma and J. Hu, Reseller or Market? E-platform strategy under blockchain-enabled recycling. *Expert Syst. App.* **243** (2024) 122811.

[31] Q. Lu, C. Liao and X. Chen, The blockchain adoption strategies of online retailer in a dual-channel supply chain. *Int. J. Prod. Econ.* **274** (2024) 109322.

[32] C. Lutz, B. Meyer, C. Nathani and J. Schleich, Endogenous technological change and emissions: the case of the german steel industry. *Energy Policy* **33** (2005) 1143–1154.

[33] D. Ma, H. Qin and J. Hu, Achieving triple sustainability in closed-loop supply chain: the optimal combination of online platform sales format and blockchain-enabled recycling. *Comput. Ind. Eng.* **174** (2022) 108763.

[34] A. Mardani, D. Kannan, R.E. Hooker, S. Ozkul, M. Alrasheedi and E.B. Tirkolaee, Evaluation of green and sustainable supply chain management using structural equation modelling: a systematic review of the state of the art literature and recommendations for future research. *J. Clean. Prod.* **249** (2020) 119383.

[35] A. Mondal and S.K. Roy, Multi-objective sustainable opened- and closed-loop supply chain under mixed uncertainty during COVID-19 pandemic situation. *Comput. Ind. Eng.* **159** (2021) 107453.

[36] A. Mondal, B.K. Giri, S.K. Roy, M. Deveci and D. Pamucar, Sustainable-resilient-responsive supply chain with demand prediction: an interval type-2 robust programming approach. *Eng. App. Artif. Intell.* **133** (2024) 108133.

[37] A.K. Mukherjee, G. Maity, J. Jablonsky, S.K. Roy and G.W. Weber, A sustainable inventory optimisation considering imperfect production under uncertain environment. *Int. J. Syst. Sci. Oper. Logistics* **11** (2024) 2379540.

[38] A. Paul, M. Pervin, S.K. Roy, G.W. Weber and A. Mirzazadeh, Effect of price-sensitive demand and default risk on optimal credit period and cycle time for a deteriorating inventory model. *RAIRO-Oper. Res.* **55** (2021) S2575–S2592.

[39] M. Pournader, Y. Shi, S. Seuring and S.C.L. Koh, Blockchain applications in supply chains, transport and logistics: a systematic review of the literature. *Int. J. Prod. Res.* **58** (2020) 2063–2081.

[40] H. Pun, J.M. Swaminathan and P. Hou, Blockchain adoption for combating deceptive counterfeits. *Prod. Oper. Manage.* **30** (2021) 864–882.

[41] S. Saberi, M. Kouhizadeh and J. Sarkis, Blockchain technology: a panacea or pariah for resources conservation and recycling. *Res. Conserv. Recycle* **130** (2018) 80–81.

[42] B. Scholtens, The greening of finance: Integrating environmental considerations into financial decision-making. *J. Econ. Surv.* **33** (2019) 1127–1153.

[43] Y.L. Shen, S.P. Willems and Y. Dai, Channel selection and contracting in the presence of a retail platform. *Prod. Oper. Manage.* **28** (2018) 1173–1185.

[44] Y.L. Shen, X.D. Yang and Y. Dai, Manufacturer-retail platform interactions in the presence of a weak retailer. *Int. J. Prod. Res.* **57** (2019) 2732–2754.

[45] M. Shokouhifar, R. Naderi, A. Goli, P. Gultom, M.S. Nikabadi and G.W. Weber, Metaheuristic-driven extended exergy accounting for sustainable closed-loop food supply chain management. *Comput. Ind. Eng.* **191** (2024) 110148.

[46] J.D. Shulman, T.C. Anne and R.C. Savaskan, Optimal restocking fees and information provision in an integrated demand-supply model of product returns. *Manuf. Serv. Oper. Manage.* **11** (2009) 577–594.

[47] S. Smulders, M. Toman and C. Withagen, Growth theory and "green Growth". *Oxford Rev. Econ. Policy* **30** (2014) 423–446.

[48] M. Song, S. Wang and H. Zhang, Could environmental regulation and rand tax incentives affect green product innovation? *J. Clean. Prod.* **258** (2020) 120849.

[49] X. Tian, F. Bai, J. Jia, Y. Liu and F. Shi, Realizing low-Carbon development in a developing and industrializing region: impacts of industrial structure change on CO_2 emissions in southwest China. *J. Environ. Manage.* **233** (2019) 728–738.

[50] E.B. Tirkolaee, A. Goli, P. Ghasemi and F. Goodarzian, Designing a sustainable closed-loop supply chain network of face masks during the COVID-19 pandemic: pareto-based algorithms. *J. Clean. Prod.* **333** (2022) 130056.

[51] L. Wu, S. Kaneko and S. Matsuoka, Driving forces behind the stagnancy of China's energy-related CO_2 emissions from 1996 to 1999: the relative importance of structural change, intensity change and scale change. *Energy Policy* **33** (2005) 319–335.

[52] X. Xu, S. Zeng and Y. He, The impact of information disclosure on consumer purchase behavior on sharing economy platform Airbnb. *Int. J. Prod. Econ.* **231** (2021) 107846.

[53] X. Xu, P. He, L. Zhou and T.C.E. Cheng, Coordination of a platform-based supply chain in the marketplace or reselling mode considering cross-channel effect and blockchain technology. *Eur. J. Oper. Res.* **309** (2023) 170–187.

[54] D.Q. Yao, J.J. Liu and K. Liu, Supply chain coordination under agency selling and reselling: implications of price commitment. *Prod. Oper. Manage.* **27** (2018) 2131–2144.

[55] A.A. Yunis, H. Raharjo, Y. Tharyono and D.R. Insih, Green investment, firm value, and financial performance: evidence from emerging markets. *Sustainability* **13** (2021) 5272.

[56] Y. Zhang and J. Zhang, Estimating the Impacts of emissions trading scheme on low-carbon development. *J. Clean. Prod.* **238** (2019) 117913.

[57] T. Zhang, G. Li, K.K. Lai and J.W.K. Leung, Information disclosure strategies for the intermediary and competitive sellers. *Eur. J. Oper. Res.* **271** (2018) 1156–1173.

[58] Y. Zhang, J. Zhang, Y. Zhou, H. Zhao and Y. Cheng, Blockchain adoption and mode selection strategies for remanufacturing supply chain under cap-and-trade policy. *Comput. Ind. Eng.* **192** (2024) 110246.

[59] J.L. Zhao, S. Fan and J. Yan, Overview of business innovations and research opportunities in blockchain and introduction to the special issue. *Finan. Innov.* **2** (2016) 2–7.

[60] Q. Zhao, Z.P. Fan and M. Sun, Sales mode selection and blockchain technology adoption decisions in a platform supply chain. *Int. J. Prod. Econ.* **272** (2024) 109255.

[61] J.C. Zimmer, R.E. Arsal, M. Al-Marzouq and V. Grover, Investigating online information disclosure: effects of information relevance, trust and risk. *Inf. Manage.* **47** (2010) 115–123.

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Appendix A.

Proof of Mode RN. We solve this mode by backward induction. For any given wholesale price w_{RN}, we first characterize the equilibrium price p_{RN} that the platform set to maximize her profit $\pi_{\mathrm{P}}^{\mathrm{RN}}$. By taking the first- and second-order partial derivatives, we obtain $\begin{cases} \frac{\partial \pi_{\mathrm{P}}^{\mathrm{RN}}}{\partial p_{\mathrm{RN}}} = 1 - \frac{\eta e_0 + 2p_{\mathrm{RN}} + w_{\mathrm{RN}}}{\theta} \\ \frac{\partial^2 \pi_{\mathrm{P}}^{\mathrm{RN}}}{\partial {p_{\mathrm{RN}}}^2} = -\frac{2}{\theta} < 0 \end{cases}$, we derive $p_{\mathrm{RN}} = -\frac{\eta e_0 + \theta + w_{\mathrm{RN}}}{2}$. Thus, $\pi_{\mathrm{M}}^{\mathrm{RN}} = w_{\mathrm{RN}} \cdot (1 - \frac{\eta \cdot e_0 + p_{\mathrm{RN}}}{\theta}) = -\frac{w_{\mathrm{RN}}(\eta e_0 - \theta + w_{\mathrm{RN}})}{2\theta}$. By taking the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{RN}}$ with respect to w_{T}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{RN}}}{\partial w_{\mathrm{RN}}} = \frac{-\eta e_0 + \theta - 2w_{\mathrm{RN}})}{2\theta} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{RN}}}{\partial {w_{\mathrm{RN}}}^2} = -\frac{1}{\theta} < 0 \end{cases}$, we determine that the equilibrium wholesale price is $w_{\mathrm{RN}}^* = \frac{1}{2}(\theta - \eta \cdot e_0)$; thus, the equilibrium retail price is $p_{\mathrm{RN}}^* = \frac{3}{4}(\theta - \eta \cdot e_0)$. Substituting w_{RN}^* and p_{RN}^* into the profit functions, we derive $\pi_{\mathrm{M}}^{\mathrm{RN}*} = \frac{1}{8\theta}(\theta - \eta \cdot e_0)^2$, $\pi_{\mathrm{P}}^{\mathrm{RN}*} = \frac{1}{16\theta}(\theta - \eta \cdot e_0)^2$. □

Proof of Proposition 1. By taking the first- and second-order partial derivatives of $\pi_{\mathrm{T}}^{\mathrm{RT}}$ with respect to p_{RT}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{P}}^{\mathrm{RT}}}{\partial p_{\mathrm{RT}}} = 1 - \frac{\eta(e - e_0) + 2p_{\mathrm{RT}} - w_{\mathrm{RT}}}{\theta} \\ \frac{\partial^2 \pi_{\mathrm{P}}^{\mathrm{RN}}}{\partial {p_{\mathrm{RT}}}^2} = -\frac{2}{\theta} < 0 \end{cases}$, we derive $p_{\mathrm{RT}} = \frac{\eta(e - e_0) + \theta + w_{\mathrm{RN}}}{2}$. Thus, $\pi_{\mathrm{M}}^{\mathrm{RT}} = w_{\mathrm{RT}} \cdot (1 - \frac{\eta \cdot (e_0 - e_{\mathrm{RT}}) + p}{\theta}) - \frac{1}{2}{e_{\mathrm{RT}}}^2 = \frac{-{w_{\mathrm{RN}}}^2 + [\eta(e - e_0) + \theta] w_{\mathrm{RN}} - {e_{\mathrm{RT}}}^2 \theta}{2\theta}$. By taking the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{RT}}$ with respect to w_{RT}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}}}{\partial w_{\mathrm{RT}}} = \frac{\eta(e - e_0) + \theta - 2w_{\mathrm{RT}}}{2\theta} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{RT}}}{\partial {w_{\mathrm{RT}}}^2} = -\frac{1}{\theta} < 0 \end{cases}$, we determine that the wholesale price is $w_{\mathrm{RN}}^* = \frac{1}{2}[\theta + \eta(e - e_0)]$. We then substitute the above results in $\pi_{\mathrm{M}}^{\mathrm{RT}}$ and take the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{RT}}$ with respect to e_{RT}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}}}{\partial e_{\mathrm{RT}}} = \frac{\eta^2(e - e_0) + (\eta - 4e_0)\theta}{4\theta} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{RT}}}{\partial {e_{\mathrm{RT}}}^2} = \frac{\eta^2}{4\theta} - 1 \end{cases}$, when satisfy $4\theta - \eta^2 > 0$, $e_{\mathrm{RT}}^* = \frac{\eta(\eta e_0 - \theta)}{\eta^2 - 4\theta}$. Substituting it into p_{RT} and w_{RT}, we derive $w_{\mathrm{RT}}^* = \frac{2\theta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2}$. $p_{\mathrm{RT}}^* = \frac{3\theta \cdot (\theta - \eta \cdot e_0)}{4\theta - \eta^2}$. Substituting e_{RT}^*, w_{RT}^* and p_{RT}^* into the profit functions, we derive $\pi_{\mathrm{M}}^{\mathrm{RT}*} = \frac{1}{2(4\theta - \eta^2)}(\theta - \eta \cdot e_0)^2$, $\pi_{\mathrm{P}}^{\mathrm{RT}*} = \frac{\theta}{(4\theta - \eta^2)^2}(\theta - \eta \cdot e_0)^2$. □

Proof of Proposition 2. Taking the first- and second-order partial derivatives of $\pi_{\mathrm{P}}^{\mathrm{RB}}$ with respect to p_{RB}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{P}}^{\mathrm{RB}}}{\partial p_{\mathrm{RB}}} = \alpha I + \eta(e - e_0) - 2p_{\mathrm{RB}} + w_{\mathrm{RB}} + 1 \\ \frac{\partial^2 \pi_{\mathrm{P}}^{\mathrm{RB}}}{\partial {p_{\mathrm{RB}}}^2} = -2 < 0 \end{cases}$, we derive $p_{\mathrm{RB}} = \frac{\eta(e - e_0) + \alpha I + w_{\mathrm{RN}} + 1}{2}$. Thus, $\pi_{\mathrm{M}}^{\mathrm{RB}} = w_{\mathrm{RB}} \cdot [1 - \eta \cdot (e_0 - e_{\mathrm{RB}}) + \alpha \cdot I - p_{\mathrm{RB}}] - \frac{1}{2}{e_{\mathrm{RB}}}^2 = \frac{-{w_{\mathrm{RB}}}^2 + [\eta(e - e_0) + \theta] w_{\mathrm{RN}} - {e_{\mathrm{RB}}}^2}{2\theta}$. By taking the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{RB}}$ with respect to w_{RB}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{RB}}}{\partial w_{\mathrm{RB}}} = \frac{\eta(e - e_0) + \alpha I - 2w_{\mathrm{RB}} + 1}{2} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{RB}}}{\partial {w_{\mathrm{RB}}}^2} = -1 < 0 \end{cases}$, we determine that the wholesale price

is $w_{\mathrm{RB}} = \frac{1}{2}[\alpha I + \eta(e - e_0) + 1]$. We substitute the above results in $\pi_{\mathrm{P}}^{\mathrm{RB}}$ and take the first- and second-order partial derivatives of $\pi_{\mathrm{P}}^{\mathrm{RB}}$ with respect to I_{RB}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{P}}^{\mathrm{RB}}}{\partial I_{\mathrm{RB}}} = \frac{\alpha^2 I + \alpha[\eta(e-e_0)+1]}{8} - I \\ \frac{\partial^2 \pi_{\mathrm{P}}^{\mathrm{RB}}}{\partial {I_{\mathrm{RB}}}^2} = \frac{\alpha^2}{8} - 1 < 0 \end{cases}$, we derive $I_{\mathrm{RB}} = -\frac{\alpha[\eta(e-e_0)+1]}{\alpha^2-8}$. We then substitute the above results in $\pi_{\mathrm{M}}^{\mathrm{RB}}$ and take the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{RB}}$ with respect to e_{RB}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{RB}}}{\partial e_{\mathrm{RB}}} = \frac{16\eta(1-\eta e_0) - e[(\alpha^2-8)^2 - 16\eta^2]}{(\alpha^2-8)^2} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{RB}}}{\partial {e_{\mathrm{RB}}}^2} = -\frac{(\alpha^2-8)^2 - 16\eta^2}{(\alpha^2-8)^2} \end{cases}$, when satisfy $(\alpha^2-8)^2 - 16\eta^2 > 0$, $e_{\mathrm{RB}}^* = \frac{16\eta\cdot(1-\eta\cdot e_0)}{(\alpha^2-8)^2-16\eta^2}$. Substituting it into p_{RB}, w_{RB} and I_{RB}, we derive $w_{\mathrm{RB}}^* = \frac{4(\alpha^2-8)\cdot(\eta\cdot e_0-1)}{(\alpha^2-8)^2-16\eta^2}$, $p_{\mathrm{RB}}^* = \frac{6(\alpha^2-8)\cdot(\eta\cdot e_0-1)}{(\alpha^2-8)^2-16\eta^2}$, $I_{\mathrm{RB}}^* = \frac{\alpha(\alpha^2-8)\cdot(\eta\cdot e_0-1)}{(\alpha^2-8)^2-16\eta^2}$. Substituting e_{RB}^*, w_{RB}^*, p_{RB}^* and I_{RB}^* into the profit functions, we derive $\pi_{\mathrm{M}}^{\mathrm{RB}*} = \frac{8(\eta\cdot e_0-1)^2}{(\alpha^2-8)^2-16\eta^2}$, $\pi_{\mathrm{P}}^{\mathrm{RB}*} = \frac{-(\alpha^2-8)^3\cdot(\eta\cdot e_0-1)^2}{2[(\alpha^2-8)^2-16\eta^2]^2}$. □

Proof of Mode AN. Solving this mode for a given proportion fee γ, we use the first and second order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{AN}}$ with respect to p_{AN}, and obtain $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{AN}}}{\partial p_{\mathrm{AN}}} = -\frac{(1-\gamma)(\eta e_0 + 2p_{\mathrm{AN}} - \theta)}{\theta} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{AN}}}{\partial {p_{\mathrm{AN}}}^2} = -\frac{2(1-\gamma)}{\theta} < 0 \end{cases}$. We derive the equilibrium retail price $p_{\mathrm{AN}}^* = \frac{1}{2}(\theta - \eta\cdot e_0)$. Substituting it into the profit functions, we have $\pi_{\mathrm{M}}^{\mathrm{AN}*} = \frac{1}{4\theta}(1-\gamma)\cdot(\theta - \eta\cdot e_0)^2$, $\pi_{\mathrm{P}}^{\mathrm{AN}*} = \frac{1}{4\theta}\gamma\cdot(\theta - \eta\cdot e_0)^2$. □

Proof of Proposition 3. For given γ, taking the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{AT}}$ with respect to p_{AT}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}}}{\partial p_{\mathrm{AT}}} = -\frac{(1-\gamma)[\theta + \eta(e-e_0) - 2p_{\mathrm{AN}}]}{\theta} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{AT}}}{\partial {p_{\mathrm{AT}}}^2} = -\frac{2(1-\gamma)}{\theta} < 0 \end{cases}$. We can derive the equilibrium retail price $p_{\mathrm{AT}} = \frac{\eta(e-e_0)+\theta}{2}$. By taking the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{AT}}$ with respect to e_{RT}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}}}{\partial e_{\mathrm{AT}}} = \frac{\eta^2(1-\gamma)(e-e_0) + \theta\eta(1-\gamma) - 2\eta e_0}{2\theta} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{AT}}}{\partial {e_{\mathrm{AT}}}^2} = \frac{\eta^2(1-\gamma)}{2\theta} - 1 \end{cases}$, when satisfy $\eta^2(1-\gamma) - 2\theta < 0$, $e_{\mathrm{AT}}^* = \frac{\eta(1-\gamma)\cdot(\theta - \eta\cdot e_0)}{\eta^2(\gamma-1)+2\theta}$. Substituting it into p_{AT}, we derive $p_{\mathrm{AT}}^* = \frac{\theta\cdot(\theta - \eta\cdot e_0)}{\eta^2(\gamma-1)+2\theta}$. Substituting e_{AT}^* and p_{AT}^* into the profit functions, we derive $\pi_{\mathrm{M}}^{\mathrm{AT}*} = \frac{(1-\gamma)\cdot(\theta-\eta\cdot e_0)^2}{2[\eta^2(\gamma-1)+2\theta]}$, $\pi_{\mathrm{P}}^{\mathrm{AT}*} = \frac{\gamma\theta\cdot(\theta-\eta\cdot e_0)^2}{[\eta^2(\gamma-1)+2\theta]^2}$. □

Proof of Proposition 4. Taking the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{AB}}$ with respect to p_{AB}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{AB}}}{\partial p_{\mathrm{AB}}} = (1-\gamma)[\eta(e-e_0) + \alpha I - 2p_{\mathrm{AB}} + 1] \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{AB}}}{\partial {p_{\mathrm{AB}}}^2} = -2(1-\gamma) < 0 \end{cases}$, we derive $p_{\mathrm{AB}} = \frac{\eta(e-e_0)+\alpha I+1}{2}$. By taking the first- and second-order partial derivatives of $\pi_{\mathrm{P}}^{\mathrm{AB}}$ with respect to I_{AB}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{P}}^{\mathrm{AB}}}{\partial I_{\mathrm{AB}}} = \frac{\gamma\alpha^2 I + \gamma[\eta(e-e_0)+1]}{2} - I \\ \frac{\partial^2 \pi_{\mathrm{P}}^{\mathrm{AB}}}{\partial {I_{\mathrm{AB}}}^2} = \frac{\alpha^2\gamma}{2} - 1 < 0 \end{cases}$, we derive $I_{\mathrm{AB}} = -\frac{\alpha\gamma[\eta(e-e_0)+1]}{\alpha^2\gamma-2}$. We then substitute the above results in $\pi_{\mathrm{M}}^{\mathrm{AB}}$ and take the first- and second-order partial derivatives of $\pi_{\mathrm{M}}^{\mathrm{AB}}$ with respect to e_{AB}, we have $\begin{cases} \frac{\partial \pi_{\mathrm{M}}^{\mathrm{AB}}}{\partial e_{\mathrm{AB}}} = \frac{2(1-\gamma)(e-e_0)\eta^2 + (1-\gamma)\eta - e(\alpha^2\gamma-2)^2}{(\alpha^2\gamma-2)^2} \\ \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{AB}}}{\partial {e_{\mathrm{AB}}}^2} = \frac{-(\alpha^2\gamma-2)^2 + 2\eta^2(1-\gamma)}{(\alpha^2\gamma-2)^2} \end{cases}$, when satisfy $(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma) > 0$, $e_{\mathrm{AB}}^* = \frac{2\eta(1-\gamma)\cdot(1-\eta\cdot e_0)}{(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)}$. Substituting it into p_{AB}, and I_{AB}, we derive $p_{\mathrm{AB}}^* = \frac{(\alpha^2\gamma-2)\cdot(\eta\cdot e_0-1)}{(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)}$, $I_{\mathrm{AB}}^* = \frac{\alpha\gamma(\alpha^2\gamma-2)\cdot(\eta\cdot e_0-1)}{(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)}$. Substituting e_{RB}^*, p_{RB}^* and I_{RB}^* into the profit functions, we derive $\pi_{\mathrm{M}}^{\mathrm{AB}*} = \frac{(1-\gamma)\cdot(\eta\cdot e_0-1)^2}{(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)}$, $\pi_{\mathrm{P}}^{\mathrm{AB}*} = \frac{-\gamma(\alpha^2\gamma-2)^3\cdot(\eta\cdot e_0-1)^2}{2[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$. □

Proof of Lemma 1. (1) $\frac{\partial e_{\mathrm{RT}}^*}{\partial\theta} = \frac{\eta^2(4e_0-\eta)}{(4\theta-\eta^2)^2}$. Thus, $\frac{\partial e_{\mathrm{RT}}^*}{\partial\theta} > 0$ if $\eta \le 4e_0$, $\frac{\partial e_{\mathrm{RT}}^*}{\partial\theta} < 0$ if $\eta > 4e_0$.

$\frac{\partial w_{\mathrm{RT}}^*}{\partial\theta} = \frac{2[\eta^2(\eta e_0 - 2\theta) + 4\theta^2]}{(4\theta-\eta^2)^2}$, $\frac{\partial p_{\mathrm{RT}}^*}{\partial\theta} = \frac{3[\eta^2(\eta e_0 - 2\theta) + 4\theta^2]}{(4\theta-\eta^2)^2}$. $\eta^2(\eta e_0 - 2\theta) + 4\theta^2$ is a quadratic function of θ, which opens up and has positive values when $\theta = 0$ and $\theta = 1$. When $\eta \le 4e_0$, $\Delta \le 0$, thus $\eta^2(\eta e_0 - 2\theta) + 4\theta^2 \ge 0$. When $\eta \le 4e_0$, there is two roots in the feasible region. Thus, if $\frac{1}{4}(\eta^2 - \eta\sqrt{\eta^2 - 4\eta e_0}) < \theta < \frac{1}{4}(\eta^2 + \eta\sqrt{\eta^2 - 4\eta e_0})$, it has negative value, and has positive value otherwise.

$\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \theta} = \frac{(\eta e_0-\theta)(\eta^2-2\eta e_0-2\theta)}{(4\theta-\eta^2)^2}$, $\eta^2-2\eta e_0-2\theta$ is a liner function of θ and monotonically decreases. When $\eta \le 2e_0$, it is always negative. When $\eta > 2e_0$, it is positive if $\theta < \frac{1}{2}\eta(\eta-e_0)$ and negative otherwise.

$\frac{\pi_{\mathrm{P}}^{\mathrm{RT}*}}{\partial \theta} = \frac{(\eta e_0-\theta)[\eta^2(\eta e_0-3\theta)+4\theta(\eta e_0+\theta)]}{(4\theta-\eta^2)^3}$, $\eta^2(\eta e_0-3\theta)+4\theta(\eta e_0+\theta)$ is a quadratic function of θ, $\Delta = 9(\eta-e_0)(9\eta-4e_0)$. When $\frac{4}{9}e_0 \le \eta \le 4e_0$, $\Delta \le 0$, it is always positive. When $\eta < \frac{4}{9}e_0$ and $\eta > 4e_0$, $\Delta > 0$, thus, it is negative if $\frac{1}{8}(3\eta-4e_0-\sqrt{9\eta^2-40\eta e_0+16{e_0}^2}) < \theta < \frac{1}{8}(3\eta-4e_0+\sqrt{9\eta^2-40\eta e_0+16{e_0}^2})$ and is positive otherwise.

(2) $\frac{\partial e_{\mathrm{RT}}^*}{\partial \eta} = \frac{\theta(\eta^2-8\eta e_0+4\theta)}{(4\theta-\eta^2)^2}$, $\eta^2-8\eta e_0+4\theta$ is a liner function of θ and monotonically decreases. When $\eta \le 8e_0$, it is always negative. When $\eta > 8e_0$, it is positive if $\theta < \frac{1}{4}\eta(\eta-8e_0)$ and negative otherwise.

$\frac{\partial w_{\mathrm{RT}}^*}{\partial \eta} = \frac{2\theta[2\theta(\eta-2e_0)-\eta^2 e_0]}{(4\theta-\eta^2)^2}$, $\frac{\partial p_{\mathrm{RT}}^*}{\partial \eta} = \frac{3\theta[2\theta(\eta-2e_0)-\eta^2 e_0]}{(4\theta-\eta^2)^2}$, $\frac{\pi_{\mathrm{P}}^{\mathrm{RT}*}}{\partial \eta} = \frac{-2\theta(\eta e_0-\theta)[2\theta(\eta-2e_0)-\eta^2 e_0]}{(4\theta-\eta^2)^3}$. $2\theta(\eta-2e_0)-\eta^2 e_0$ is a liner function of e_0, which is monotonically decreases and has positive value when $e_0 = 0$ and negative value when $e_0 = 1$. Thus, when $0 < e_0 \le \frac{2\theta\eta}{\eta^2+4\theta}$, it is positive and when $\frac{2\theta\eta}{\eta^2+4\theta} < e_0 < 1$, it is negative.

$\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RT}*}}{\partial \eta} = \frac{\theta(\eta e_0-\theta)(4e_0-\eta)}{(4\theta-\eta^2)^2}$. $(\eta e_0-\theta)(4e_0-\eta)$ is a liner function of θ. When $\eta \ge 4e_0$, it is monotonically increases and is negative when $\theta \le \eta e_0$. When $\eta < 4e_0$, it is monotonically decreases and is positive when $\theta \le \eta e_0$. □

Proof of Lemma 2. (1) $\frac{\partial e_{\mathrm{RB}}^*}{\partial \eta} = \frac{16(1-2\eta e_0)\alpha^4-256(1-2\eta e_0)\alpha^2+256(\eta^2-8\eta e_0+4)}{[(\alpha^2-8)^2-16\eta^2]^2}$, $16(1-2\eta e_0)\alpha^4-256(1-2\eta e_0)\alpha^2+256(\eta^2-8\eta e_0+4)$ is a quadratic function of η which opens up and $\Delta < 0$. Thus, $\frac{\partial e_{\mathrm{RB}}^*}{\partial \eta} > 0$.

$\frac{\partial I_{\mathrm{RB}}^*}{\partial \eta} = \frac{\alpha(\alpha^2-8)[e_0(\alpha^2-8)^2+16\eta(\eta e_0-2)]}{[(\alpha^2-8)^2-16\eta^2]^2}$, $\frac{\partial w_{\mathrm{RB}}^*}{\partial \eta} = \frac{4(\alpha^2-8)[e_0(\alpha^2-8)^2+16\eta(\eta e_0-2)]}{[(\alpha^2-8)^2-16\eta^2]^2}$, $\frac{\partial p_{\mathrm{RB}}^*}{\partial \eta} = \frac{6(\alpha^2-8)[e_0(\alpha^2-8)^2+16\eta(\eta e_0-2)]}{[(\alpha^2-8)^2-16\eta^2]^2}$.

$\frac{\pi_{\mathrm{P}}^{\mathrm{RB}*}}{\partial \eta} = \frac{(1-\eta e_0)(\alpha^2-8)^3\{[(\alpha^2-8)^2+16\eta^2]e_0-32\eta\}}{[(\alpha^2-8)^2-16\eta^2]^3}$. $e_0(\alpha^2-8)^2+16\eta(\eta e_0-2)$ is a quadratic function of η which opens up and $\Delta = 16-{e_0}^2(\alpha^2-8)^2$. When, ${e_0}^2(\alpha^2-8)^2 \ge 16$, it is positive. When ${e_0}^2(\alpha^2-8)^2 < 16$, it has two roots in the feasible region. Thus, it is negative when $\frac{4+\sqrt{16-{e_0}^2(\alpha^2-8)^2}}{4e_0} < \eta < \frac{4-\sqrt{16-{e_0}^2(\alpha^2-8)^2}}{4e_0}$, otherwise it is positive.

$\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RB}*}}{\partial \eta} = \frac{(1-\eta e_0)[256\eta-16e_0(\alpha^2-8)^2]}{[(\alpha^2-8)^2-16\eta^2]^2}$, $256\eta-16e_0(\alpha^2-8)^2$ is a liner function of η which monotonically increases and have negative value when $\eta = 0$. Thus, it is positive when $\eta \ge \frac{1}{16}e_0(\alpha^2-8)^2$ and is negative otherwise.

(2) $\frac{\partial e_{\mathrm{RB}}^*}{\partial \alpha} = -\frac{64\alpha\eta(1-\eta e_0)(\alpha^2-8)}{[(\alpha^2-8)^2-16\eta^2]^2} > 0$, $\frac{\partial I_{\mathrm{RB}}^*}{\partial \alpha} = \frac{(1-\eta e_0)(\alpha^6-8\alpha^4+48\alpha^2\eta^2-64\alpha^2-128\eta^2+512)}{[(\alpha^2-8)^2-16\eta^2]^2}$, $(\alpha^6-8\alpha^4+48\alpha^2\eta^2-64\alpha^2-128\eta^2+512)$ has positive value in the feasible region. Thus, $\frac{\partial I_{\mathrm{RB}}^*}{\partial \alpha} > 0$. $\frac{\partial w_{\mathrm{RB}}^*}{\partial \alpha} = \frac{8\alpha(1-\eta e_0)[(\alpha^2-8)^2+16\eta^2]}{[(\alpha^2-8)^2-16\eta^2]^2} > 0$, $\frac{\partial p_{\mathrm{RB}}^*}{\partial \alpha} = \frac{12\alpha(1-\eta e_0)[(\alpha^2-8)^2+16\eta^2]}{[(\alpha^2-8)^2-16\eta^2]^2} > 0$, $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{RB}*}}{\partial \alpha} = -\frac{32\alpha(\alpha^2-8)(1-\eta e_0)^2}{[(\alpha^2-8)^2-16\eta^2]^2} > 0$, $\frac{\pi_{\mathrm{P}}^{\mathrm{RB}*}}{\partial \alpha} = \frac{\alpha(\alpha^2-8)^2(1-\eta e_0)^2[(\alpha^2-8)^2+48\eta^2]}{[(\alpha^2-8)^2-16\eta^2]^3} > 0$.

□

Proof of Lemma 3. (1) $\frac{\partial e_{\mathrm{AT}}^*}{\partial \theta} = \frac{\eta^2(1-\gamma)[2e_0-\eta(1-\gamma)]}{[\eta^2(\gamma-1)+2\theta]^2} > 0$, $\frac{\partial p_{\mathrm{AT}}^*}{\partial \theta} = \frac{\eta^2(1-\gamma)(\eta e_0-2\theta)+2\theta^2}{[\eta^2(\gamma-1)+2\theta]^2}$, $\eta^2(1-\gamma)(\eta e_0-2\theta)+2\theta^2$ is a quadratic function of θ which opens up and $\Delta = 4\eta^3(\gamma-1)[2e_0-(1-\gamma)\eta]$. When $e_0 \ge \frac{1}{2}\eta(1-\gamma)$, $\Delta < 0$, it is always positive. But when $e_0 < \frac{1}{2}\eta(1-\gamma)$, it has two roots in the feasible region. Thus, when $\frac{1}{2}\{\eta(1-\gamma)-\sqrt{\eta(1-\gamma)[2e_0+\eta(1-\gamma)]}\} < \theta < \frac{1}{2}\{\eta(1-\gamma)-\sqrt{\eta(1-\gamma)[2e_0+\eta(1-\gamma)]}\}$, it is negative and is positive otherwise.

$\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}*}}{\partial \theta} = \frac{(1-\gamma)(\eta e_0-\theta)[\eta^2(1-\gamma)-(\eta e_0+\theta)]}{[\eta^2(\gamma-1)+2\theta]^2}$, $\eta^2(1-\gamma)-(\eta e_0+\theta)$ is a liner function of θ which monotonically decreases. When $e_0 \ge \eta(1-\gamma)$, it is always negative. When $e_0 < \eta(1-\gamma)$, it is positive if $\theta < \eta^2(1-\gamma)-\eta e_0$, otherwise it is negative.

$\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial \theta} = \frac{\gamma(\eta e_0-\theta)[\eta^2(1-\gamma)(3\theta-\eta e_0)-2\theta(\eta e_0+\theta)]}{[\eta^2(\gamma-1)+2\theta]^3}$, $\eta^2(1-\gamma)(3\theta-\eta e_0)-2\theta(\eta e_0+\theta)$ is a quadratic function of θ which opens down. When $\eta(1-\gamma) \le 2e_0 \le 9\eta(1-\gamma)$, $\Delta \le 0$, it is always negative. When $2e_0 > 9\eta(1-\gamma)$ *or* $2e_0 < \eta(1-\gamma)$, $\Delta > 0$, it has two feasible solutions in the feasible region. Thus, when $\frac{1}{4}\{3\eta(1-\gamma)-2e_0-\sqrt{9\eta^2(1-\gamma)^2+4e_0[e_0-5\eta(1-\gamma)]}\} < \theta < \frac{1}{4}\{3\eta(1-\gamma)-2e_0+\sqrt{9\eta^2(1-\gamma)^2+4e_0[e_0-5\eta(1-\gamma)]}\}$, it is positive and is negative otherwise.

(2) $\frac{\partial e_{\mathrm{AT}}^*}{\partial \eta} = \frac{(1-\gamma)\theta[\eta^2(1-\gamma)-2(\eta e_0-\theta)]}{[\eta^2(\gamma-1)+2\theta]^2}$, $\eta^2(1-\gamma)-2(\eta e_0-\theta)$ is a quadratic function of η which opens up. When $2{e_0}^2 \le \theta(1-\gamma)$, $\Delta \le 0$, it is always positive. When $2{e_0}^2 > \theta(1-\gamma)$, $\Delta > 0$, it has two solutions in the feasible region. Thus, when $\frac{2e_0-\sqrt{4{e_0}^2-2\theta(1-\gamma)}}{1-\gamma} < \eta < \frac{2e_0+\sqrt{4{e_0}^2-2\theta(1-\gamma)}}{1-\gamma}$, it is negative and is positive otherwise.

$\frac{\partial p_{\mathrm{AT}}^{*}}{\partial \eta}=\frac{\theta[(1-\gamma)\eta(2\theta-\eta e_0)-2\theta e_0]}{[\eta^2(\gamma-1)+2\theta]^2}$, $(1-\gamma)\eta(2\theta-\eta e_0)-2\theta e_0$ is a quadratic function of η which opens up. When $2{e_0}^2\leq\theta(1-\gamma)$, $\Delta\leq 0$, it is always positive. When $2{e_0}^2>\theta(1-\gamma)$, $\Delta>0$, it has two solutions in the feasible region. Thus, when $\frac{\theta(1-\gamma)-\sqrt{\theta(1-\gamma)[\theta(1-\gamma)-2{e_0}^2]}}{e_0(1-\gamma)}<\eta<\frac{\theta(1-\gamma)+\sqrt{\theta(1-\gamma)[\theta(1-\gamma)-2{e_0}^2]}}{e_0(1-\gamma)}$, it is negative and is positive otherwise.

$\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AT}*}}{\partial \eta}=\frac{\theta(\eta e_0-\theta)(1-\gamma)[2e_0-\eta(1-\gamma)]}{[\eta^2(\gamma-1)+2\theta]^2}$, $2e_0-\eta(1-\gamma)$ is a liner function of η which monotonically decreases and has positive value when $\eta=0$. When $2e_0\leq\eta(1-\gamma)$, it is always negative and is positive otherwise.

$\frac{\pi_{\mathrm{P}}^{\mathrm{AT}*}}{\partial \eta}=\frac{2\theta\gamma(\eta e_0-\theta)[\eta(1-\gamma)(\eta e_0-2\theta)-2\theta e_0]}{[\eta^2(\gamma-1)+2\theta]^3}$, $\eta(1-\gamma)(\eta e_0-2\theta)-2\theta e_0$ is a quadratic function of η which opens up. When $2{e_0}^2\leq\theta(1-\gamma)$, $\Delta\leq 0$, it is always negative. When $2{e_0}^2>\theta(1-\gamma)$, $\Delta>0$, it has two solution in the feasible region. Thus, when $\frac{\theta(1-\gamma)-\sqrt{\theta(1-\gamma)[\theta(1-\gamma)-2{e_0}^2]}}{e_0(1-\gamma)}<\eta<\frac{\theta(1-\gamma)+\sqrt{\theta(1-\gamma)[\theta(1-\gamma)-2{e_0}^2]}}{e_0(1-\gamma)}$, it is positive and is negative otherwise. □

Proof of Lemma 4. (1) $\frac{\partial e_{\mathrm{AB}}^{*}}{\partial \eta}=\frac{(1-\gamma)\{(1-2\eta e_0)\alpha^4-[2\eta^2(1-2\eta e_0)+\eta^2]\gamma-(\eta^2-4\eta e_0-2)\}}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$, the part in the biggest bracket is a quadratic function of η, which opens negative and negative value when $\eta=0$, we bring $\eta=1$ into this function and derives that it is positive. Thus, when $0\leq\eta\leq\frac{(2-\alpha^2\gamma)[e_0(2-\alpha^2\gamma)+\sqrt{{e_0}^2(2-\alpha^2\gamma)^2+2(\gamma-1)}]}{2(1-\gamma)}$, $\frac{\partial e_{\mathrm{AB}}^{*}}{\partial \eta}\leq 0$, otherwise $\frac{\partial e_{\mathrm{AB}}^{*}}{\partial \eta}>0$.

$\frac{\partial I_{\mathrm{AB}}^{*}}{\partial \eta}=\frac{\alpha\gamma(\alpha^2\gamma-2)[\alpha^4\gamma^2e_0+\gamma(-4\alpha^2e_0-2\eta^2e_0+4\eta)+2\eta^2e_0-4\eta+4e_0]}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$, $\frac{\partial p_{\mathrm{AB}}^{*}}{\partial \eta}=\frac{(\alpha^2\gamma-2)[\alpha^4\gamma^2e_0+\gamma(-4\alpha^2e_0-2\eta^2e_0+4\eta)+2\eta^2e_0-4\eta+4e_0]}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$, and $\frac{\pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial \eta}=\frac{(1-\eta e_0)\gamma(\alpha^2-8)^3[\alpha^4\gamma^2e_0+\gamma(-4\alpha^2e_0-2\eta^2e_0+4\eta)+2\eta^2e_0-4\eta+4e_0]}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$. They have the same part in the square blanket. It is a quadratic function of η which opens up and is positive when $\eta=0$. $\Delta=4(\gamma-1)[2{e_0}^2(\alpha^2\gamma-2)^2+(\gamma-1)]$. When $e_0\leq\frac{\sqrt{2(1-\gamma)}}{\alpha^2\gamma-2}$, the function has positive value. When $e_0>\frac{\sqrt{2(1-\gamma)}}{\alpha^2\gamma-2}$, it has roots in the feasible region. When $e_0>\frac{4(1-\gamma)}{(\alpha^2\gamma-2)^2+2(1-\gamma)}$, it is positive when $\eta=1$. Then, when $\frac{2(1-\gamma)-\sqrt{2\alpha^2\gamma^2{e_0}^2[\alpha^2(\gamma-1)-4]+8\gamma{e_0}^2(\alpha^2+1)+4[(\gamma-1)^2-2{e_0}^2]}}{2e_0(1-\gamma)}\leq\eta\leq\frac{2(1-\gamma)+\sqrt{2\alpha^2\gamma^2{e_0}^2[\alpha^2(\gamma-1)-4]+8\gamma{e_0}^2(\alpha^2+1)+4[(\gamma-1)^2-2{e_0}^2]}}{2e_0(1-\gamma)}$, it is negative, otherwise positive. When $\frac{\sqrt{2(1-\gamma)}}{\alpha^2\gamma-2}<e_0<\frac{4(1-\gamma)}{(\alpha^2\gamma-2)^2+2(1-\gamma)}$, it is negative when $\eta=1$. Then, when $\eta\geq\frac{2(1-\gamma)-\sqrt{2\alpha^2\gamma^2{e_0}^2[\alpha^2(\gamma-1)-4]+8\gamma{e_0}^2(\alpha^2+1)+4[(\gamma-1)^2-2{e_0}^2]}}{2e_0(1-\gamma)}$, it is positive, otherwise negative.

$\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AB}*}}{\partial \eta}=\frac{2(1-\gamma)(\eta e_0-1)[(\alpha^2\gamma-2)^2e_0-2(1-\gamma)\eta]}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$, the part in the square bracket is a simple function of e_0. When $e_0\geq\frac{2\eta(1-\gamma)}{(\alpha^2\gamma-2)^2}$, it is positive, otherwise negative.

(2) $\frac{\partial e_{\mathrm{AB}}^{*}}{\partial \alpha}=\frac{8\alpha\gamma\eta(1-\gamma)(\eta e_0-1)(\alpha^2\gamma-2)}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}>0$.

$\frac{\partial I_{\mathrm{AB}}^{*}}{\partial \alpha}=\frac{(1-\eta e_0)\gamma[\alpha^6\gamma^3-2\alpha^4\gamma^2+6\alpha^2\eta^2\gamma-4(\alpha^2\gamma-\eta^2\gamma+\eta^2-2)]}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$, the part in the square bracket is a quadratic function of η and the constant term and the value of this function when $\eta=1$ are both positive, so this function always has positive value in the feasible region of η. Thus, $\frac{\partial I_{\mathrm{AB}}^{*}}{\partial \alpha}>0$.

$\frac{\partial p_{\mathrm{AB}}^{*}}{\partial \alpha}=\frac{2\alpha\gamma(1-\eta e_0)[\alpha^4\gamma^2-2\gamma(2\alpha^2+\eta^2)+2\eta^2+4]}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$, the part in the square bracket is a quadratic function of α^2 which opens up and $\Delta=-8(1-\gamma)\gamma^2\eta^2<0$. Thus, $\frac{\partial p_{\mathrm{AB}}^{*}}{\partial \alpha}>0$.

$\frac{\partial \pi_{\mathrm{M}}^{\mathrm{AB}*}}{\partial \alpha}=\frac{4\alpha\gamma(\gamma-1)(\alpha^2\gamma-2)(1-\eta e_0)^2}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}>0$.

$\frac{\partial \pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial \alpha}=\frac{\alpha\gamma^2(\alpha^2\gamma-2)^2(1-\eta e_0)^2[(\alpha^2-2)^2-6\eta^2(1-\gamma)]}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}$, the part in the square bracket is a quadratic function of α^2 which opens up and $\Delta=-24(1-\gamma)\gamma^2\eta^2<0$. Thus, $\frac{\partial \pi_{\mathrm{P}}^{\mathrm{AB}*}}{\partial \alpha}>0$. □

Proof of Proposition 5. We compare the manufacturer's profits in Modes RN, RT and RB ($\pi_{\mathrm{M}}^{\mathrm{RN}*}$, $\pi_{\mathrm{M}}^{\mathrm{RT}*}$ and $\pi_{\mathrm{M}}^{\mathrm{RB}*}$).

First, we have $\pi_{\mathrm{M}}^{\mathrm{RT}*}-\pi_{\mathrm{M}}^{\mathrm{RN}*}=\frac{-\eta^2(\eta e_0-\theta)^2}{8\theta(\eta^2-4\theta)}>0$. Thus, $\pi_{\mathrm{M}}^{\mathrm{RT}*}>\pi_{\mathrm{M}}^{\mathrm{RN}*}$.

Then, we have $\pi_{\mathrm{M}}^{\mathrm{RB}*}-\pi_{\mathrm{M}}^{\mathrm{RN}*}=\frac{1}{8\theta[(\alpha^2-8)^2-16\eta^2]}f_1(\theta)$, where $f_1(\theta)=(A\theta^2+B\theta+C)$, $A=-[(\alpha^2-8)^2-16\eta^2]<0$, $B=2\eta e_0(\alpha^4-16\alpha^2-16\eta^2+32\eta e_0)+64>0$, and $C=-\eta^2{e_0}^2(\alpha^4-16\alpha^2-16\eta^2+64)<0$. Besides, $\Delta=-4096(\eta e_0-1)^2[\eta e_0(-\frac{1}{16}\alpha^4+\eta^2+\alpha^2-2)-\eta^2{e_0}^2-1]>0$ and $f_1(\theta=1)=(\eta e_0-1)^2(-\alpha^4+16\alpha^2+16\eta^2)>0$. Thus, $f_1(\theta)$ opens down and has only one roots in the feasible region, that is $\theta_1^{*}=$

$\frac{1}{16\eta^2-(\alpha^2-8)^2}\{32(1-\eta e_0)\sqrt{[1+\eta^2{e_0}^2+\eta e_0(\frac{1}{16}\alpha^4-\eta^2-\alpha^2+2)]}+16\eta^3e_0-32\eta^2{e_0}^2-\alpha^2\eta e_0(\alpha^2-16)-32\}$. Generally, $\pi_{\mathrm{M}}^{\mathrm{RB}*}\le\pi_{\mathrm{M}}^{\mathrm{RN}*}$ when $0<\theta\le\theta_1^*$, $\pi_{\mathrm{M}}^{\mathrm{RB}*}>\pi_{\mathrm{M}}^{\mathrm{RN}*}$ when $\theta_1^*<\theta<1$.

Besides, we have $\pi_{\mathrm{M}}^{\mathrm{RB}*}-\pi_{\mathrm{M}}^{\mathrm{RT}*}=\frac{1}{2(\eta^2-4\theta)[(\alpha^2-8)^2-16\eta^2]}f_2(\theta)$, where $f_2(\theta)=(D\theta^2+E\theta+F)$, $D=[(\alpha^2-8)^2-16\eta^2]>0$, $E=-2\eta e_0(\alpha^4-16\alpha^2-16\eta^2+32\eta e_0)-64<0$, $F=\eta^2{e_0}^2(\alpha^2-8)^2+16\eta^2(1-\eta e_0)>0$. Besides, $\Delta=1024(\eta e_0-1)^2[\frac{1}{4}\eta e_0(\alpha^4-16\alpha^2+32)-\eta^2(4{e_0}^2-\frac{1}{16}(\alpha^2-8)^2-1]>0$ and $f_2(\theta=1)=\alpha^2(\eta e_0-1)^2(\alpha^2-8)<0$. Thus, $f_2(\theta)$ opens up and has only one roots in the feasible region, that is $\theta_2^*=\frac{1}{16\eta^2-(\alpha^2-8)^2}\{16(1-\eta e_0)\sqrt{\frac{1}{4}\eta e_0(\alpha^4-16\alpha^2+32)+\eta^2[(4{e_0}^2-\frac{1}{16}(\alpha^2-8)^2]+\eta^4-4\eta^3e_0+4}\}+16\eta^3e_0-32\eta^2{e_0}^2-\alpha^2\eta e_0(\alpha^2-16)-32$. Generally, $\pi_{\mathrm{M}}^{\mathrm{RB}*}\le\pi_{\mathrm{M}}^{\mathrm{RT}*}$ when $0<\theta\le\theta_2^*$, $\pi_{\mathrm{M}}^{\mathrm{RB}*}>\pi_{\mathrm{M}}^{\mathrm{RT}*}$ when $\theta_2^*<\theta<1$.

Comparing θ_1^* and θ_2^*, we have $\theta_1^*<\theta_2^*$. Summarily, $\pi_{\mathrm{M}}^{\mathrm{RT}*}>\pi_{\mathrm{M}}^{\mathrm{RN}*}>\pi_{\mathrm{M}}^{\mathrm{RB}*}$ when $0<\theta<\theta_1^*$, $\pi_{\mathrm{M}}^{\mathrm{RT}*}>\pi_{\mathrm{M}}^{\mathrm{RB}*}>\pi_{\mathrm{M}}^{\mathrm{RN}*}$ when $\theta_1^*<\theta<\theta_2^*$, $\pi_{\mathrm{M}}^{\mathrm{RB}*}>\pi_{\mathrm{M}}^{\mathrm{RT}*}>\pi_{\mathrm{M}}^{\mathrm{RN}*}$ when $\theta_2^*<\theta<1$. □

Proof of Proposition 6. We compare the manufacturer's profits in Modes AN, AT and AB ($\pi_{\mathrm{M}}^{\mathrm{AN}*}$, $\pi_{\mathrm{M}}^{\mathrm{AT}*}$ and $\pi_{\mathrm{M}}^{\mathrm{AB}*}$).

First, we have $\pi_{\mathrm{M}}^{\mathrm{AT}*}-\pi_{\mathrm{M}}^{\mathrm{AN}*}=\frac{\eta^2(\eta e_0-\theta)^2(\gamma-1)^2}{4\theta[(\gamma-1)\eta^2+2\theta)}>0$. Thus, $\pi_{\mathrm{M}}^{\mathrm{AT}*}>\pi_{\mathrm{M}}^{\mathrm{AN}*}$.

Then, we have $\pi_{\mathrm{M}}^{\mathrm{AB}*}-\pi_{\mathrm{M}}^{\mathrm{AN}*}=\frac{\gamma-1}{4\theta[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]}f_3(\theta)$, where $f_3(\theta)=(G\theta^2+H\theta+I)$, $G=(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)>0$, $H=-2\eta e_0[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]+2(\eta e_0-2)<0$, and $I=\eta^2{e_0}^2[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]>0$. Besides, $f_3(\theta=1)=(\eta e_0-1)^2[\alpha^2\gamma(\alpha^2\gamma-4)-2\eta^2(1-\gamma)]<0$. Thus, $f_3(\theta)$ opens up and has only one roots in the feasible region, that is $\theta_3^*=\frac{1}{(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)}[2e_0(\gamma-1)\eta^3+2\eta^2{e_0}^2+\eta e_0\alpha^2\gamma(\alpha^2\gamma-4)+2+2(1-\eta e_0)\sqrt{1+\eta^2{e_0}^2+\eta e_0[\alpha^2\gamma(\alpha^2\gamma-4)-2\eta^2(1-\gamma)-2]}$. Generally, $\pi_{\mathrm{M}}^{\mathrm{AB}*}\le\pi_{\mathrm{M}}^{\mathrm{AN}*}$ when $0<\theta\le\theta_3^*$, $\pi_{\mathrm{M}}^{\mathrm{AB}*}>\pi_{\mathrm{M}}^{\mathrm{AN}*}$ when $\theta_3^*<\theta<1$.

Besides, we have $\pi_{\mathrm{M}}^{\mathrm{AB}*}-\pi_{\mathrm{M}}^{\mathrm{AT}*}=\frac{\gamma-1}{2[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)][\eta^2(\gamma-1)+2\theta]}f_4(\theta)$, where $f_4(\theta)=(J\theta^2+K\theta+L)$, $J=[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]>0$, $K=-2\eta e_0[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]+2(\eta e_0-2)<0$, $L=\eta^2{e_0}^2[(\alpha^2\gamma-2)^2+2\eta^2(\eta e_0-1)(\gamma-1)]>0$. Besides, $f_4(\theta=1)=\alpha^2\gamma(\eta e_0-1)^2(\alpha^2\gamma-4)<0$. Thus, $f_4(\theta)$ opens up and has only one roots in the feasible region, that is $\theta_4^*=\frac{1}{(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)}\{2\eta^3e_0(\gamma-1)+2\eta^2{e_0}^2+\alpha^2\gamma\eta e_0(\alpha^2-4)-\sqrt{2}\sqrt{(\eta e_0-1)^2\{2+2(\gamma-1)^2\eta^4+4e_0\eta^3(\gamma-1)+[(2{e_0}^2+(\gamma-1)(\alpha^2\gamma-2)^2]\eta^2+2e_0(\alpha^4\gamma^2-4\alpha^2\gamma+2)\}}\}$. Generally, $\pi_{\mathrm{M}}^{\mathrm{AB}*}\le\pi_{\mathrm{M}}^{\mathrm{AT}*}$ when $0<\theta\le\theta_4^*$, $\pi_{\mathrm{M}}^{\mathrm{AB}*}>\pi_{\mathrm{M}}^{\mathrm{AT}*}$ when $\theta_4^*<\theta<1$.

Comparing θ_3^* and θ_3^*, we have $\theta_3^*<\theta_4^*$. Summarily, $\pi_{\mathrm{M}}^{\mathrm{AT}*}>\pi_{\mathrm{M}}^{\mathrm{AN}*}>\pi_{\mathrm{M}}^{\mathrm{AB}*}$ when $0<\theta<\theta_3^*$, $\pi_{\mathrm{M}}^{\mathrm{AT}*}>\pi_{\mathrm{M}}^{\mathrm{AB}*}>\pi_{\mathrm{M}}^{\mathrm{AN}*}$ when $\theta_3^*<\theta<\theta_4^*$, $\pi_{\mathrm{M}}^{\mathrm{AB}*}>\pi_{\mathrm{M}}^{\mathrm{AT}*}>\pi_{\mathrm{M}}^{\mathrm{AN}*}$ when $\theta_4^*<\theta<1$. □

Proof of Proposition 7. We compare the platform's profits in Modes RN, RT and RB ($\pi_{\mathrm{P}}^{\mathrm{RN}*}$, $\pi_{\mathrm{P}}^{\mathrm{RT}*}$ *and* $\pi_{\mathrm{P}}^{\mathrm{RB}*}$).

First, we have $\pi_{\mathrm{P}}^{\mathrm{RT}*}-\pi_{\mathrm{P}}^{\mathrm{RN}*}=\frac{-\eta^2(\eta e_0-\theta)^2(\eta^2-8)}{16\theta(\eta^2-4\theta)^2}>0$. Thus, $\pi_{\mathrm{P}}^{\mathrm{RT}*}>\pi_{\mathrm{P}}^{\mathrm{RN}*}$.

Then, we have $\pi_{\mathrm{P}}^{\mathrm{RB}*}-\pi_{\mathrm{P}}^{\mathrm{RN}*}=\frac{1}{16\theta[(\alpha^2-8)^2-16\eta^2]^2}h_1(\theta)$, where $h_1(\theta)=(A\theta^2+B\theta+C)$, $A=-[(\alpha^2-8)^2-16\eta^2]^2<0$, $B=-8(\alpha^2-8)^3(\eta^2{e_0}^2+1)+2\eta e_0[2\alpha^8-24\alpha^6+(192-32\eta^2)\alpha^4+512(\eta^2-1)\alpha^2+256\eta^2(\eta^2-8)]>0$, and $C=-\eta^2{e_0}^2[(\alpha^2-8)^2-16\eta^2]^2<0$. Besides, $h_1(\theta=1)=-(\eta e_0-1)^2(256\eta^4-32(\alpha^2-8)^2\eta^2+\alpha^2(\alpha^2-8)^3)>0$. Thus, $h_1(\theta)$ opens down and has only one roots in the feasible region, that is $\theta_5^*=\frac{1}{[(\alpha^2-8)^2-16\eta^2]^2}\{\eta e_0\alpha^8-(4\eta^2{e_0}^2+24\eta e_0+4)\alpha^6-32(\eta^3e_0-3\eta^2{e_0}^2-6\eta e_0-3)\alpha^4+256(2\eta^3e_0-3\eta^2{e_0}^2-2\eta e_0-3)\alpha^2+256(\eta^5e_0-8\eta^3e_0+8\eta^2{e_0}^2+8)-2(1-\eta e_0)\sqrt{(\alpha^2-8)^3\{2\eta^2{e_0}^2(\alpha^2-8)^3-\eta e_0[\eta^4-64\eta^2(\alpha^2-8)^2+2(\alpha^2-4)(\alpha^2-8)^3]+4(\alpha^2-8)^3\}}\}$. Generally, $\pi_{\mathrm{P}}^{\mathrm{RB}*}\le\pi_{\mathrm{P}}^{\mathrm{RN}*}$ when $0<\theta\le\theta_5^*$, $\pi_{\mathrm{P}}^{\mathrm{RB}*}>\pi_{\mathrm{P}}^{\mathrm{RN}*}$ when $\theta_5^*<\theta<1$.

Besides, we have $\pi_{\mathrm{P}}^{\mathrm{RB}*}-\pi_{\mathrm{P}}^{\mathrm{RT}*}=\frac{1}{2(\eta^2-4\theta)^2[(\alpha^2-8)^2-16\eta^2]^2}h_2(\theta)$, where $h_2(\theta)=(D\theta^3+E\theta^2+F\theta+G)$, $D=-[512\eta^4+64(\alpha^2-8)^2\eta^2-2(\alpha^2-8)^4]<0$, $E=1024\eta^5e_0-128\eta^3e_0(\alpha^2-8)^2-16\eta^2{e_0}^2(\alpha^2-8)^3+4\eta e_0\alpha^2(\alpha^2-8)^3-16(\alpha^2-8)^3>0$, $F=-512\eta^6{e_0}^2+8\alpha^2\eta^4{e_0}^2(\alpha^2-8)^2-16\eta^3e_0(\alpha^2-8)^3-2\eta^2(\alpha^2-8)^3(\alpha^2{e_0}^2-8{e_0}^2-4)<0$, $G=-(\alpha^2-8)^3\eta^4(\eta e_0-1)^2<0$. Besides, $\Delta=1024(\eta e_0-1)^2[\frac{1}{4}\eta e_0(\alpha^4-16\alpha^2+32)-\eta^2(4{e_0}^2-\frac{1}{16}(\alpha^2-8)^2-1]>0$ and $h_2(\theta=1)=-\alpha^2(\eta-1)^2[(\alpha^4-24\alpha^2+192)\eta^4-8(\alpha^2-8)^2\eta^2+2(\alpha^2-8)^3>0$. According to the properties of cubic functions, $h_2(\theta)$ has only one roots in the feasible region, that is θ_6^*. Because of the complexity of expression of θ_6^*, we do not give the expression but θ_6^* is indeed a feasible solution of $h_2(\theta)$ in the feasible region $[0,1]$. Generally, $\pi_{\mathrm{P}}^{\mathrm{RB}*}\le\pi_{\mathrm{P}}^{\mathrm{RT}*}$ when $0<\theta\le\theta_6^*$, $\pi_{\mathrm{P}}^{\mathrm{RB}*}>\pi_{\mathrm{P}}^{\mathrm{RT}*}$ when $\theta_6^*<\theta<1$.

Comparing θ_5^* and θ_6^*, we have $\theta_5^*<\theta_6^*$. Summarily, $\pi_{\mathrm{P}}^{\mathrm{RT}*}>\pi_{\mathrm{P}}^{\mathrm{RN}*}>\pi_{\mathrm{P}}^{\mathrm{RB}*}$ when $0<\theta<\theta_5^*$, $\pi_{\mathrm{P}}^{\mathrm{RT}*}>\pi_{\mathrm{P}}^{\mathrm{RB}*}>\pi_{PM}^{\mathrm{RN}*}$ when $\theta_5^*<\theta<\theta_6^*$, $\pi_{\mathrm{P}}^{\mathrm{RB}*}>\pi_{\mathrm{P}}^{\mathrm{RT}*}>\pi_{\mathrm{P}}^{\mathrm{RN}*}$ when $\theta_6^*<\theta<1$. □

Proof of Proposition 8. We compare the platform's profits in Modes AN, AT and AB ($\pi_P^{AN^*}$, $\pi_P^{AT^*}$ *and* $\pi_P^{AB^*}$).

First, we have $\pi_P^{AT^*} - \pi_P^{AN^*} = \frac{\gamma\eta^2(\eta e_0-\theta)^2(1-\gamma)[\eta^2(\gamma-1)+4\theta]}{4\theta[(\gamma-1)\eta^2+2\theta)} > 0$. Thus, $\pi_P^{AT^*} > \pi_P^{AN^*}$.

Then, we have $\pi_P^{AB^*} - \pi_P^{AN^*} = \frac{-\gamma}{4\theta[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}h_3(\theta)$, where $h_3(\theta) = (H\theta^2 + I\theta + J)$, $H = [(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma)]^2 > 0$, $I = -8\eta^5 e_0(1-\gamma)^2 + 8\eta^3 e_0(\alpha^2\gamma-2)^2(1-\gamma) + 2(\alpha^2\gamma-2)^3(\eta^2 {e_0}^2 - \gamma\eta e_0\alpha^2 + 1) < 0$, and $J = \eta^2 {e_0}^2[(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma)]^2 > 0$. Besides, $h_3(\theta = 1) = (\eta e_0 - 1)^2[4\eta^4(1-\gamma)^2 - 4(1-\gamma)(\alpha^2\gamma-2)^2\eta^2 + \alpha^2\gamma(\alpha^2\gamma-2)^3] < 0$. Thus, $h_3(\theta)$ opens up and has only one roots in the feasible region, that is $\theta_7^* = \frac{1}{[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2}\{[\alpha^8\gamma^4\eta e_0 - \alpha^6\gamma^3(\eta^2 {e_0}^2 + 6\eta e_0 + 1) + 2\alpha^4\gamma^2[3 - 2\eta^3 e_0(1-\gamma) + 3\eta^2 {e_0}^2 + 6\eta e_0] - 4\alpha^2\gamma[3 - 4\eta^3 e_0(1-\gamma) + 12\eta^2 {e_0}^2 + 2\eta e_0] + 4\eta^5 e_0(1-\gamma)^2 - 16\eta^3 e_0(1-\gamma) + 8\eta^2 {e_0}^2 + 8 - (1-\eta e_0)\sqrt{-(\alpha^2\gamma-2)^3\{\eta^2 {e_0}^2(\alpha^2\gamma-2)^3 + 2\eta e_0[4\eta^4(1-\gamma)^2 + (\alpha^2\gamma-2)^2[(\alpha^2\gamma-2)^2 - 4\eta^2(1-\gamma)]\}}$. Generally, $\pi_P^{AB^*} \leq \pi_P^{AN^*}$ when $0 < \theta \leq \theta_7^*$, $\pi_P^{AB^*} > \pi_P^{AN^*}$ when $\theta_7^* < \theta < 1$.

Besides, we have $\pi_P^{AB^*} - \pi_P^{AT^*} = \frac{-\gamma}{2[(\alpha^2\gamma-2)^2-2\eta^2(1-\gamma)]^2[\eta^2(\gamma-1)+2\theta]^2}h_4(\theta)$, where $h_4(\theta) = (K\theta^3 + L\theta^2 + M\theta + N)$, $K = 2[(\alpha^2\gamma-2)^2 - 2\eta^2(1-\gamma)]^2 > 0$, $N = \eta^4(1-\gamma)^2(\eta e_0 - 1)^2(\alpha^2\gamma-2)^3 < 0$. By calculating, we obtain that $h_4(\theta)$ monotonically decreases in $[0,1]$. Besides, $h_4(\theta = 1) = \alpha^2\gamma(\eta e_0 - 1)^2[\eta^4(1-\gamma)^2(\alpha^4\gamma^2 - 6\alpha^2\gamma + 12) - 4\eta^2(1-\gamma)(\alpha^2\gamma-2)^2 + 2(\alpha^2\gamma-2)^3] < 0$. Thus, $h_4(\theta)$ always has negative value in the feasible region. Generally, $\pi_P^{AB^*} > \pi_P^{AT^*}$.

Summarily, $\pi_P^{AT^*} > \pi_P^{AN^*} > \pi_P^{AB^*}$ when $0 < \theta < \theta_7^*$, $\pi_P^{AB^*} > \pi_P^{AT^*} > \pi_P^{AN^*}$ when $\theta_4^* < \theta < 1$. □