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Research article

Platform traffic support, quality improvement, and carbon emission reduction under agency and reselling modes

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Abstract: E-commerce platforms provide traffic support to products included in low-carbon zones, yet how this strategy affects manufacturers' quality improvement, carbon emission reduction, and outcomes under different sales modes remains unclear. We develop a manufacturer-led feedback Stackelberg differential game with green goodwill as the dynamic state variable to compare six operational cases combining traffic support, low-carbon, and traditional models with the reselling and agency modes. The numerical results show that compared with the low-carbon model without traffic support, traffic support strengthens the manufacturer's quality improvement and carbon emission reduction efforts, accelerates green goodwill accumulation, and increases both supply chain members' payoff values. In contrast, introducing carbon emission reduction without traffic support increases green goodwill but has a relatively small incremental effect on the manufacturer's quality improvement effort and payoff value. The numerical results show that agency selling yields higher quality improvement effort, green goodwill, and manufacturer payoff values across the three models. Retail price rankings depend on the commission rate and each mode's green goodwill. Carbon emission reduction effort is also higher under agency selling in the traffic support and low-carbon models, whereas reselling induces stronger platform traffic support in the traffic support model. In both the traffic support and low-carbon models, the platform's payoff value ranking shifts from an initial reselling advantage to a subsequent agency advantage; in the traditional model, reselling consistently yields higher platform payoff values. Furthermore, a higher traffic support cost coefficient weakens the manufacturer's quality improvement and carbon emission reduction efforts. These findings inform traffic support and sales mode decisions concerning effort incentives, green goodwill, and firm payoffs.

Keywords: traffic support; e-commerce platform; carbon emission reduction effort; sales mode; green goodwill
Mathematics Subject Classification: 90B06, 91A23, 91A65

1. Introduction

With the rapid development of the digital economy, e-commerce platforms have become crucial hubs for goods circulation and consumer behavior, profoundly influencing consumers' decisions and business operations through large-scale traffic portals and algorithmic recommendation mechanisms. Numerous cases have shown that platforms provide traffic support to specific products or sellers through optimized search rankings, homepage recommendations, dedicated zones, and green labels, thereby guiding consumers' preferences, improving conversion rates, and enhancing brand exposure. Typical examples include Amazon's "Climate Pledge Friendly" program and Walmart's "Built for Better" program. By displaying green certification labels and providing traffic support, these mechanisms increase the visibility and sales of environmentally friendly products and encourage brands to adopt higher green standards. According to Capterra's 2022 Consumer Sustainability Expectations Survey of 759 US consumers, 88% of respondents checked a product's sustainability at least sometimes before making a purchase [1]. Accordingly, an increasing number of consumers are paying attention to the low-carbon attributes of products, prompting e-commerce platforms in both domestic and international markets to explore green and low-carbon business models.

Platform traffic support has evolved from a simple commercial promotion tool into an important resource allocation mechanism. By leveraging big data and algorithmic recommendations, platforms enhance the market visibility of green products through low-carbon zones, green labels, and targeted exposure. Consequently, manufacturers' investments in carbon emission reduction affect not only production costs but also product exposure, consumers' purchase intentions, and sales revenue, thereby changing their competitive positions in the market. In a low-carbon zone with traffic support, the disclosure of verifiable information on the manufacturer's carbon emission reduction effort may affect current demand and thereby change how the manufacturer allocates its efforts between quality improvement and carbon emission reduction. As consumers increasingly value both product quality and low-carbon attributes, platforms also consider product quality when implementing traffic support. Against this background, examining manufacturers' carbon emission reduction and quality improvement decisions under different sales modes and low-carbon-zone participation regimes helps explain their effort incentives, green goodwill accumulation, and the payoffs of platforms and manufacturers.

Furthermore, the choice of sales mode has a profound impact on incentive mechanisms, profit distribution, and green behavior strategies on both the supply and demand sides. Reselling and agency modes are common sales models on platforms [2,3]. Under the reselling mode, the platform has the pricing power and assumes the inventory risk, whereas under the agency mode, the platform mainly earns commission income while the manufacturer controls the retail price. The two modes therefore differ substantially in terms of green investment, marketing strategies, and the platform's response mechanisms to traffic support. Studies have shown that, owing to differences in the power structures between the platform and the manufacturer, manufacturers' green investment under different sales modes significantly affects the profit distribution between the platform and the manufacturer, as well as the market response [4]. Accordingly, this paper provides a detailed analysis of the reselling and agency modes and the resulting outcomes under alternative low-carbon-zone participation regimes.

Although platform traffic support, green goodwill accumulation, carbon emission reduction, and product quality improvement have attracted increasing attention, their dynamic interactions with sales

mode selection remain insufficiently explored. In particular, a systematic analysis of how platform traffic support affects manufacturers' quality improvement and carbon emission reduction decisions and supply chain members' payoffs is still lacking. To address this gap, we consider a supply chain consisting of one manufacturer and one platform and develop a manufacturer-led Stackelberg differential game. Using green goodwill as the dynamic state variable, we examine the interactions among traffic support, quality improvement, carbon emission reduction, and sales mode. Specifically, we develop three models: The traffic support model, the low-carbon model, and the traditional model. In the traffic support model, the manufacturer is assumed to operate within the low-carbon zone, undertakes both quality improvement and carbon emission reduction efforts, and receives traffic support from the platform. In the low-carbon model, the manufacturer is assumed to operate outside the low-carbon zone, undertakes both efforts, and receives no platform traffic support. In the traditional model, the manufacturer undertakes only quality improvement effort. Combining each model with the reselling and agency modes yields six operational cases, providing a unified dynamic framework for comparing the effects of traffic support, carbon emission reduction, and sales mode on equilibrium decisions, green goodwill, and the payoffs of both parties.

By comparing the six equilibrium cases across the traffic support, low-carbon, and traditional models under the reselling and agency modes, we examine supply chain members' equilibrium decisions, the dynamic evolution of green goodwill, and both parties' payoffs to clarify the effects of low-carbon-zone participation and the associated traffic support, as well as the manufacturer's carbon emission reduction strategy. Specifically, we address the following three research questions:

1. What are the manufacturer's and the platform's equilibrium pricing and investment strategies under the reselling and agency modes in each of the three models?
2. How do equilibrium decisions, green goodwill dynamics, retail prices, and both parties' payoff values differ across the three models and between the two sales modes? Under what parameter conditions do the corresponding rankings hold? How do the payoff rankings evolve over time?
3. How do key model parameters, including the effect coefficients governing green goodwill formation and the traffic support cost coefficient, affect equilibrium effort levels, green goodwill, and both parties' payoff values under different sales modes? How does the direct effect of carbon emission reduction effort on current-period demand alter the manufacturer's relative investment in quality improvement and carbon emission reduction?

This study makes three main contributions. First, it identifies the additional incentives provided by traffic support in the low-carbon zone for the manufacturer's quality improvement and carbon emission reduction efforts. Under the specified parameter values, numerical comparisons show that the traffic support model yields greater quality improvement and carbon emission reduction efforts, faster green goodwill accumulation, and higher payoff values for both parties than the low-carbon model without traffic support.

Second, this study reveals how sales mode shapes the incentives for platform traffic support and manufacturer efforts differently. The numerical results show that the platform provides a higher traffic support level under the reselling mode, whereas the manufacturer's greater quality improvement and carbon emission reduction efforts under the agency mode lead to higher green goodwill and manufacturer payoff values. Moreover, the platform's payoff ranking between the two sales modes may reverse as green goodwill accumulates.

Third, this study clarifies how the coefficients governing green goodwill formation and the platform's traffic support cost coefficient affect the manufacturer's quality improvement and carbon emission reduction efforts, green goodwill, and both parties' payoff values. The sensitivity analysis shows that increases in the effect coefficients of quality improvement, carbon emission reduction, and traffic support on green goodwill increase green goodwill and both parties' payoff values. In particular, a higher effect coefficient of traffic support on green goodwill also increases the manufacturer's quality improvement and carbon emission reduction efforts, whereas a higher traffic support cost coefficient reduces both efforts.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and highlights the contributions of this study. Section 3 develops the theoretical model. Sections 4–6 derive the equilibrium solutions for the traffic support, low-carbon, and traditional models. Section 7 provides analytical equilibrium comparisons and examines sales mode and retail price rankings. Section 8 presents the numerical comparisons, a sensitivity analysis, and a parameter robustness analysis. Section 9 develops the extended model. Finally, Section 10 concludes the paper and outlines directions for future research.

2. Literature review

Our study draws on four streams of literature: Platform traffic support, sales mode selection, carbon emission reduction, and quality improvement.

2.1. Platform traffic support

Existing studies generally indicate that subsidies constitute a core strategy in the platform economy for optimizing resource allocation, incentivizing participation, and enhancing performance [5,6]. Their applications span multiple contexts, including market competition [6], shared logistics [7], community group buying [8], and cooperative promotion in online retail platforms [9]. In quality-sensitive domains such as digital content platforms, the literature has further evolved from general price subsidies to quality-contingent support mechanisms. For example, Jain and Qian [10] found that user tipping schemes incentivize platforms to increase revenue sharing with content creators, thereby improving the content's quality. Gao et al. [11] explicitly compared traffic-based support with monetary subsidies and showed that traffic support more directly enhances content quality and, under certain conditions, generates a "win–win" outcome for both the platform and producers.

However, the existing literature exhibits notable limitations. First, prior research has predominantly focused on traditional platform settings, such as digital content and shared logistics, while paying limited attention to the platform's traffic support for merchants entering the low-carbon zone, leaving the underlying mechanisms in this specific context underexplored. Second, although recent studies have begun to examine subsidy schemes in green supply chains (e.g., [12]), research on platform-led traffic support strategies that simultaneously incentivize manufacturers to achieve the dual objectives of carbon emission reduction and quality improvement remains scarce.

2.2. Sales mode selection

The choice between the reselling mode and the agency mode in platform supply chains has become a focal issue in operations management literature. A substantial body of research has examined the

underlying decision mechanisms from perspectives such as supplier competition [13], information services [14], channels' power [15], and advertising strategies [16]. For instance, Abhishek et al. [17] showed that a platform's sales mode choice is influenced by the demand spillover effect of online sales on traditional channels. Zhang and Zhang [18] further demonstrated that suppliers' threats of offline channel encroachment significantly alter the platform's information-sharing strategies under the two modes. In recent years, increasing attention has been devoted to the roles of environmental sustainability and technological innovation in shaping sales mode choice. In the context of green supply chains, Xu et al. [3] found that a platform-led reselling mode is more conducive to improving the product's greenness level, whereas a manufacturer-led reselling mode better enhances the manufacturer's own profit. Li et al. [4] showed that heightened consumer environmental awareness encourages manufacturers to adopt the agency mode. Regarding product quality, Zhao et al. [19] investigated the role of blockchain technology and found that the agency mode provides stronger incentives for manufacturers to adopt blockchain to enhance the credibility of product quality.

Building on these studies, we examine the interaction between the platform's traffic support and sales mode choice when manufacturers undertake both quality improvement and carbon emission reduction. Although Xu et al. [3] and Yu et al. [20] considered carbon trading and carbon tax policies, and Li et al. [4] and Zhao et al. [19] focused on green products and product quality, none of these studies incorporated traffic subsidies as an endogenous decision variable of the platform. Such proactive incentive schemes may alter the manufacturer's payoff structure between sustainable investment and channel selection, thereby reshaping the optimal logic of sales mode choice. Therefore, this study aims to fill this gap. Compared with the existing literature, we develop a theoretical model to investigate how manufacturers' investment strategies in carbon emission reduction and quality improvement influence the sales mode choice when the platform establishes a dedicated zone and provides traffic support.

2.3. Carbon emission reduction and quality improvement

Existing studies have fully demonstrated the important roles of carbon emission reduction and product quality management in supply chain operations. Research on carbon emission reduction shows that firms' emission reduction behavior not only satisfies environmental regulatory requirements but also improves the supply chain's performance and market competitiveness by satisfying consumers' low-carbon preferences [21–24]. Further studies from the perspective of supply chain coordination have found that cooperative mechanisms can effectively improve emission reduction levels, environmental benefits, and economic returns [21,22,25]. At the same time, product quality, as an important factor affecting market share and firms' profitability, is closely related to pricing, the channel structure, and market information in firms' decision-making processes [26–28]. In multichannel operational contexts, scholars have further examined the effects of buy-online-and-pick-up-in-store (BOPS) channels, channel encroachment, and quality improvement strategies on firms' decisions and performance [29–31].

However, most existing studies focus on traditional supply chain settings and pay insufficient attention to the mechanism through which platforms actively guide manufacturers' behavior by establishing low-carbon zones and implementing traffic support. Although some studies involve platform contexts – for example, Zhang et al. [32] analyzed the impact of platform contracts on quality decisions, and Yu et al. [33] explored the role of blockchain technology in low-carbon supply chains – the former did not consider low-carbon attributes, while the latter focused on technological empowerment rather than platform incentives. Therefore, this paper focuses on the platform's low-carbon zone and traffic support mechanism and examines its coordinated impact on manufacturers' carbon emission reduction and product quality decisions, thereby filling the research gap at the intersection of platform-led sustainable operations and quality competition.

3. Problem description

This section is organized as follows. First, we present the basic structure of the model, including the decision variables and the notation. Second, we explain the mathematical specifications and economic meanings of the green goodwill dynamics, demand function, and cost functions. Finally, we present the decision sequence and describe the six cases obtained by combining the three models with the reselling mode and the agency mode.

3.1. Decision variables and notations

To promote the low-carbon transition and high-quality development of platform products, and to optimize the platform's governance environment, platform enterprises implement traffic support programs to incentivize manufacturers to produce green and high-quality products. To analyze the current situation of products on the platform, this study develops a dynamic game model of a supply chain composed of a platform and a manufacturer, in which the manufacturer sells products on the platform under both the agency mode and the reselling mode. Let $t \in [0, +\infty)$ denote the continuous time. Under the agency mode, the manufacturer sells products directly to consumers by paying a commission fee to the platform. In practice, the commission rate for products within the same category is typically predetermined and remains fixed. For example, Amazon charges a 7% commission rate for consumer electronics, 14% for office products, and 10% for software [34]. This practice is reasonable because platforms serve a large number of manufacturers offering diverse products, making it impractical to customize commission rates individually. Therefore, a uniform commission rate by category is commonly adopted [4]. The related literature also treats the commission rate φ as an exogenous and fixed parameter [35–39]. Under the reselling mode, the manufacturer sets a wholesale price $W(t)$ and sells the product to the platform, which then determines the retail price $P(t)$, $t \in [0, +\infty)$ and resells the product to consumers. Table 1 summarizes the main notation used in this paper.

Table 1. Notation.

Notation	Explanation
Indices	
m, e	Subscripts representing the manufacturer (m) and the e-commerce platform (e)
Decision variables	
$P(t)$	Retail price
$W(t)$	Wholesale price
$Q(t)$	Quality improvement effort of the manufacturer
$H(t)$	Carbon emission reduction effort of the manufacturer
$I(t)$	Traffic support level of the e-commerce platform
State variable	
$G(t)$	Green goodwill of the manufacturer in reselling mode and agency mode
Dependent variables	
D	Demand for the product
Π_e	The profit function of the e-commerce platform, $\Pi_e \in \{\Pi_e^{TR}, \Pi_e^{TA}, \Pi_e^{LR}, \Pi_e^{LA}, \Pi_e^{BR}, \Pi_e^{BA}\}$
Π_m	The profit function of the manufacturer, $\Pi_m \in \{\Pi_m^{TR}, \Pi_m^{TA}, \Pi_m^{LR}, \Pi_m^{LA}, \Pi_m^{BR}, \Pi_m^{BA}\}$
J_e	The value function of the e-commerce platform, $J_e \in \{J_e^{TR}, J_e^{TA}, J_e^{LR}, J_e^{LA}, J_e^{BR}, J_e^{BA}\}$
J_m	The value function of the manufacturer, $J_m \in \{J_m^{TR}, J_m^{TA}, J_m^{LR}, J_m^{LA}, J_m^{BR}, J_m^{BA}\}$
Abbreviations	
TR	Traffic support model, reselling mode
TA	Traffic support model, agency mode
LR	Low-carbon model, reselling mode
LA	Low-carbon model, agency mode
BR	Traditional model, reselling mode
BA	Traditional model, agency mode
QIE	Quality improvement effort
CERE	Carbon emission reduction effort
TSL	Traffic support level
Parameters	
α	Baseline market demand ($\alpha \geq 0$)
β	Consumer's sensitivity of the green goodwill ($\beta \geq 0$)
γ	Sensitivity coefficient of consumers to retail price ($\gamma > 0$)
τ	Effect coefficient of quality improvement effort on green goodwill ($\tau > 0$)
λ	Effect coefficient of carbon emission reduction effort on green goodwill ($\lambda > 0$)
ε	Effect coefficient of platform traffic support on green goodwill ($\varepsilon > 0$)
δ	Natural decay rate of green goodwill ($\delta > 0$)
η	Cost coefficient of carbon emission reduction effort ($\eta > 0$)
ξ	Cost coefficient of quality improvement effort ($\xi > 0$)
μ	Cost coefficient of traffic support ($\mu > 0$)
φ	Commission rate ($\varphi \in (0, 1)$)
c	Unit production cost
ρ	Discount rate ($\rho > 0$)

To accelerate the transition toward green and low-carbon development and improve the platform's ecosystem, the platform establishes a dedicated low-carbon product zone and increases the exposure of products in this zone to guide consumers toward sustainable consumption. We define such exposure-enhancing measures as traffic support and let $I(t)$ denote the traffic support level chosen by the platform at time t. Specifically, traffic support refers to the platform's preferential allocation of traffic resources to products offered by manufacturers participating in the low-carbon zone. It is implemented through homepage pop-up displays, priority placement in the search results, recommendation slots, algorithmic recommendations, and targeted push notifications. A higher traffic support level $I(t)$ means that the platform provides greater exposure to the manufacturer's products through these measures. For example, a higher traffic support level for an appliance in the low-carbon zone may involve more prominent placement in the search results or recommendation slots. The traffic support level $I(t)$ is determined by the platform, while the effect coefficient ε measures the contribution of the platform's traffic support to green goodwill, as specified in Section 3.2. To focus on the role of the platform's traffic support in green goodwill accumulation, we do not introduce the manufacturer's independent advertising expenditure as a separate decision variable.

In the proposed model, the manufacturer's key decision variables are quality improvement effort and carbon emission reduction effort, denoted $Q(t)$ and $H(t)$, respectively. Quality improvement effort enhances products' functionality and durability through investments in design and production processes. The manufacturer's carbon emission reduction effort, $H(t)$, captures the intensity of activities aimed at reducing product-related carbon emissions, such as adopting low-carbon technologies and improving production processes. For an appliance manufacturer, quality improvement effort may involve improving products' functionality and durability, while carbon emission reduction effort may involve adopting low-carbon production technologies. The manufacturer determines the levels of these two efforts and bears the corresponding costs. Their contributions to green goodwill are described by the effect coefficients τ and λ, respectively, while their costs are specified by the cost functions in Section 3.4.

3.2. Dynamics of green goodwill

With the continuous enhancement of consumers' environmental awareness, they not only focus on product quality but also attach increasing importance to the low-carbon attributes of products. Against this background, e-commerce platforms incentivize manufacturers to produce low-carbon products by enhancing their visibility through traffic support, thereby strengthening their green goodwill. In the traffic support model, the manufacturer's green goodwill is jointly affected by quality improvement effort, carbon emission reduction effort, and the platform's traffic support level. Since green goodwill accumulation is a dynamic process evolving over time, this study adopts a dynamic modeling approach [40]. Quality improvement effort, carbon emission reduction effort, and the platform's traffic support contribute to the accumulation of green goodwill, while existing green goodwill gradually decays over time. Consequently, current decisions affect both the current costs and future green goodwill, with the latter in turn influencing future demand. Following Nerlove and Arrow [41], Guan et al. [42], and Parilina et al. [43], the green goodwill dynamics are formulated as follows:

$$\dot{G}(t) = \tau Q(t) + \lambda H(t) + \varepsilon I(t) - \delta G(t), \quad G(0) = G^0. \tag{3.1}$$

where $G(t)$ denotes the manufacturer's green goodwill at time t, reflecting consumers' accumulated perceptions of product quality and the manufacturer's carbon emission reduction activities. The

parameters $\tau > 0$, $\lambda > 0$, and $\varepsilon > 0$ denote the effect coefficients of quality improvement effort, carbon emission reduction effort, and platform traffic support on green goodwill, respectively. The parameter $\delta > 0$ is the natural decay rate of green goodwill, and $G^0 > 0$ is the initial level of green goodwill. The terms $\tau Q(t)$, $\lambda H(t)$, and $\varepsilon I(t)$ represent the contributions of quality improvement effort, carbon emission reduction effort, and the platform's traffic support to the change in green goodwill per unit of time, respectively. The term $\delta G(t)$ represents the decrease in green goodwill due to natural decay per unit of time. Therefore, green goodwill increases when $\tau Q(t) + \lambda H(t) + \varepsilon I(t) > \delta G(t)$ and decreases when the inequality is reversed. When the two sides are equal, green goodwill remains unchanged at that time. The manufacturer's quality improvement effort $Q(t)$, carbon emission reduction effort $H(t)$, and the platform's traffic support level $I(t)$ are decision variables, while the effect coefficients τ, λ, and ε describe their respective effects on green goodwill.

3.3. Product demand

Following the existing literature [25,29,44], market demand at time t is modeled as a function of green goodwill $G(t)$ and retail price $P(t)$. As described in Section 3.2, green goodwill reflects consumers' accumulated perceptions of product quality and the manufacturer's carbon emission reduction activities. In the traffic support model, quality improvement effort, carbon emission reduction effort, and the platform's traffic support jointly contribute to goodwill accumulation. The demand effect of traffic support is captured through this goodwill stock: Preferential exposure contributes to goodwill formation, and the resulting goodwill influences demand over time. This specification focuses on the persistent demand effect of platform exposure through accumulated green goodwill. Demand is assumed to increase with green goodwill and decrease with the retail price [43,45]. Accordingly, the demand function is specified as follows:

$$D(P(t), G(t)) = \alpha + \beta G(t) - \gamma P(t), \tag{3.2}$$

where α denotes the baseline market demand, β represents the sensitivity coefficient of consumers to green goodwill, and γ denotes the sensitivity coefficient of consumers to retail price. For a given retail price, an increase of one unit in green goodwill increases demand by β. For a given level of green goodwill, an increase of one unit in the retail price decreases demand by γ. Thus, $\beta G(t)$ describes the contribution of green goodwill to demand, while $\gamma P(t)$ describes the decrease in demand associated with the retail price. For example, at the same retail price, an appliance manufacturer with higher green goodwill may obtain greater demand. In the three models, quality improvement effort, carbon emission reduction effort, and the platform's traffic support affect demand through green goodwill whenever the corresponding activity is included. The subsequent analysis considers positive demand, that is, $\alpha + \beta G(t) - \gamma P(t) > 0$. The notations $D_e(t)$ and $D_m(t)$ used below denote demand under the reselling mode and the agency mode, respectively, evaluated using this demand function.

3.4. Cost functions

In the initial stage of product production, the manufacturer's investments in product quality improvement and carbon emission reduction typically yield substantial effects. However, as the product improvement process progresses, further significant enhancements in product quality or reductions in the products' carbon emissions become increasingly difficult for the manufacturer to achieve, and the

required investment costs increase accordingly. To capture the characteristic of increasing marginal costs [25,42,43], the manufacturer's cost functions for quality improvement effort and carbon emission reduction effort are specified in quadratic forms as $C_Q(t) = \frac{\xi Q^2(t)}{2}$ and $C_H(t) = \frac{\eta H^2(t)}{2}$, respectively, where $\xi > 0$ and $\eta > 0$ denote the cost coefficients associated with quality improvement effort and carbon emission reduction effort. The marginal costs of quality improvement effort and carbon emission reduction effort are $\xi Q(t)$ and $\eta H(t)$, respectively. Both marginal costs increase with the corresponding effort level. At a given effort level, a larger cost coefficient implies a higher cost and a higher marginal cost. Therefore, these quadratic cost functions describe the increasing costs incurred by the manufacturer when increasing quality improvement effort and carbon emission reduction effort.

The platform incurs the traffic support cost $C_I(t) = \frac{\mu I^2(t)}{2}$, where $\mu > 0$ is the cost coefficient [11]. This cost represents the opportunity cost of allocating exposure resources to the focal product and the operational costs of managing their allocation. The marginal cost of traffic support is $\mu I(t)$, which increases with the traffic support level. Thus, providing additional traffic support requires the platform to bear an increasing marginal cost. The platform determines its traffic support level by considering both this cost and the future profits associated with green goodwill accumulation.

3.5. Decision sequence and six cases

This study develops a Stackelberg differential game model in which the manufacturer acts as the leader and the platform as the follower. Such a power structure is commonly adopted in studies on platform-based supply chains [17,46,47]. The manufacturer acts as the leader under both the reselling mode and the agency mode, while the decision-maker for the retail price differs between the two sales modes. Under the reselling mode, the manufacturer determines the wholesale price and its effort levels, after which the platform determines the retail price and, in the traffic support model, the traffic support level. Under the agency mode, the manufacturer determines the retail price and its effort levels, while the platform determines the traffic support level in the traffic support model. The commission rate is exogenously given. Under the feedback information structure, the decisions depend on the current level of green goodwill. Figure 1 presents the decision sequence in the six cases.

This study considers three models: The traffic support model, the low-carbon model, and the traditional model. In the traffic support model, the manufacturer undertakes both quality improvement and carbon emission reduction efforts, participates in the low-carbon zone, and receives traffic support from the platform. In the low-carbon model, the manufacturer also undertakes quality improvement and carbon emission reduction activities, but does not participate in the low-carbon zone and therefore receives no platform traffic support. In the traditional model, the manufacturer undertakes only quality improvement effort, without carbon emission reduction, participation in the low-carbon zone, or the platform's traffic support. Whether the manufacturer participates in the low-carbon zone is exogenously specified in each model. Combining the three models with the reselling mode and the agency mode yields the six cases illustrated in Figure 2. Specifically, Cases TR and TA represent the reselling and agency modes under the traffic support model, respectively; Cases LR and LA represent the reselling and agency modes under the low-carbon model, respectively; and Cases BR and BA represent the reselling and agency modes under the traditional model, respectively. For a given sales mode, the comparison between the traffic support model and the low-carbon model examines the effect of the platform's traffic support, while the comparison between the low-carbon model and the traditional model examines the effect of carbon emission reduction effort. The relevant parameters are kept the same across the

compared models, while the manufacturer and the platform determine their decisions separately in each case.

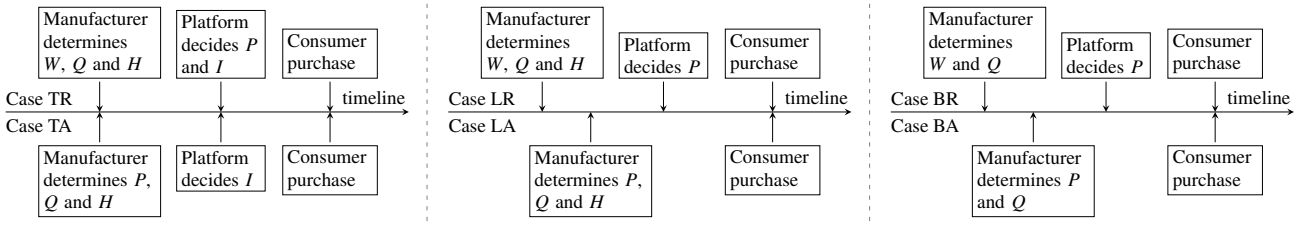


Figure 1. Decision sequence of six cases.

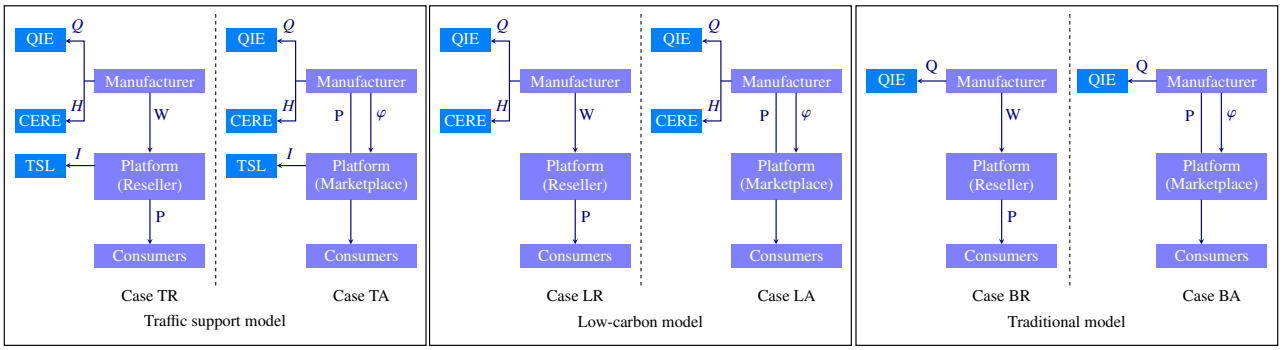


Figure 2. Structures and details in different cases.

4. Traffic support model

In this section, we derive the equilibrium outcomes under the reselling mode (Case TR) and the agency mode (Case TA) in the traffic support model. In both cases, the manufacturer undertakes quality improvement and carbon emission reduction efforts, while the platform provides traffic support. To disentangle the effects of traffic support and carbon emission reduction, Sections 5 and 6 introduce two benchmark models. Section 5 examines the low-carbon regime without traffic support, in which the manufacturer is assumed to operate outside the low-carbon zone and therefore receives no traffic support from the platform but continues to undertake both quality improvement and carbon emission reduction efforts. Low-carbon-zone participation is therefore treated as an exogenously specified operational regime rather than an endogenous binary decision of the manufacturer. Section 6 further examines the traditional model, in which neither traffic support nor carbon emission reduction is considered and the manufacturer undertakes only quality improvement effort. For ease of exposition, the superscripts TR and TA refer to Cases TR and TA, respectively, while the subscripts m and e denote the manufacturer and the platform, respectively.

4.1. Case TR

This subsection considers a manufacturer-led sequential decision-making process. Specifically, the manufacturer first determines the wholesale price $W(t)$, the quality improvement effort $Q(t)$, and the carbon emission reduction effort $H(t)$. On the basis of these decisions, the platform subsequently determines the corresponding traffic support level $I(t)$ and the retail price $P(t)$. The detailed decision sequence is illustrated in Figure 1. At time t, the manufacturer's sales revenue is $W(t)D_e(t)$, and its production cost is $cD_e(t)$. After subtracting the costs of quality improvement effort and carbon emission reduction effort, its instantaneous profit is $[W(t)-c]D_e(t)-C_Q(t)-C_H(t)$. The platform's sales revenue is $P(t)D_e(t)$, and its payment to the manufacturer is $W(t)D_e(t)$. After subtracting the cost of traffic support, its instantaneous profit is $[P(t) - W(t)]D_e(t) - C_I(t)$. Quality improvement effort, carbon emission reduction effort, and platform traffic support affect future demand through green goodwill accumulation. Therefore, both parties consider the current costs and future profits associated with their decisions. Since this study focuses on the long-term dynamic optimization problem of a low-carbon supply chain, the profit maximization problems of the manufacturer and the platform can be formulated as follows:

$$\begin{aligned} \max_{W,Q,H} \Pi_m^{TR} &= \int_0^\infty e^{-\rho t}\Big[(W(t) - c)D_e(t) - C_Q(t) - C_H(t)\Big]dt, \\ \max_{P,I} \Pi_e^{TR} &= \int_0^\infty e^{-\rho t}\Big[(P(t) - W(t))D_e(t) - C_I(t)\Big]dt, \\ \dot{G}(t) &= \tau Q(t) + \lambda H(t) + \varepsilon I(t) - \delta G(t), \quad G(0) = G^0. \end{aligned} \tag{4.1}$$

where $\rho > 0$ denotes the discount rate, and $c > 0$ is the manufacturer's unit production cost. The discount factor $e^{-\rho t}$ converts the profit at time t into its present value at time zero. For a given future profit, a higher discount rate implies a lower present value. The profit functions Π_m^{TR} and Π_e^{TR} therefore represent the discounted profits of the manufacturer and the platform over the infinite time horizon, respectively.

Under Case TR, we formulate a differential game with five decision variables (W, Q, and H for the manufacturer, and P and I for the e-commerce platform) and one state variable G. The game is solved under a feedback information structure, implying that the strategies depend on the state variable. The corresponding solution concept is the feedback Stackelberg equilibrium [48,49]. The value functions of the manufacturer and the platform are denoted by J_m^{TR} and J_e^{TR}, respectively. For a given level of green goodwill, each value function represents the present value of the corresponding firm's future profits under the equilibrium strategies, discounted to the current time. At time zero, $J_m^{TR}(G^0)$ and $J_e^{TR}(G^0)$ equal Π_m^{TR} and Π_e^{TR} evaluated under the equilibrium strategies, respectively. Thus, the value functions measure future discounted profits conditional on the current level of green goodwill. The same definitions of the profit functions and value functions apply to all six cases. In Case TR, Proposition 1 characterizes the feedback Stackelberg equilibrium strategies.

Proposition 1. *In Case TR, the unique feedback Stackelberg equilibrium strategies are given by*

$$P^{TR} = \frac{3\alpha + 3\beta G + \gamma c}{4\gamma}, \tag{4.2}$$

$$W^{TR} = \frac{\alpha + \beta G + \gamma c}{2\gamma}, \tag{4.3}$$

$$I^{TR} = \frac{\varepsilon}{\mu}\left(F_1^{TR}G + F_2^{TR}\right), \tag{4.4}$$

$$Q^{TR} = \frac{\tau}{\xi}\left(D_1^{TR}G + D_2^{TR}\right), \tag{4.5}$$

$$H^{TR} = \frac{\lambda}{\eta}\left(D_1^{TR}G + D_2^{TR}\right). \tag{4.6}$$

The value functions of the manufacturer and the platform are, respectively, given by

$$J_m^{TR} = \frac{1}{2}D_1^{TR}G^2 + D_2^{TR}G + D_3^{TR},$$
$$J_e^{TR} = \frac{1}{2}F_1^{TR}G^2 + F_2^{TR}G + F_3^{TR},$$

where the coefficients D_i^{TR} and F_i^{TR} ($i = 1, 2, 3$) are derived in the proof. The equilibrium level of green goodwill is also obtained in the proof.

Proof. See Appendix A. □

By solving the Hamilton–Jacobi–Bellman equations, we find that the value functions are quadratic in G. The equilibrium quality improvement effort satisfies the condition that the marginal cost, ξQ, equals the marginal value, $\tau\frac{dJ_m^{TR}}{dG} = \tau(D_1^{TR}G + D_2^{TR})$. Similarly, the equilibrium carbon emission reduction effort satisfies $\eta H = \lambda\frac{dJ_m^{TR}}{dG} = \lambda(D_1^{TR}G + D_2^{TR})$. The equilibrium traffic support strategy satisfies $\mu I = \varepsilon\frac{dJ_e^{TR}}{dG} = \varepsilon(F_1^{TR}G + F_2^{TR})$.

Since the coefficients of the value functions do not admit closed-form expressions, we cannot derive explicit analytical expressions for the decision variables $P(G)$ and $W(G)$ with respect to the state variable. Therefore, numerical simulations are conducted in the subsequent analysis.

4.2. Case TA

In Case TA, the manufacturer sells products through the platform marketplace. The manufacturer first determines the retail price $P(t)$, the quality improvement effort $Q(t)$, and the carbon emission reduction effort $H(t)$. On the basis of these decisions, the platform subsequently determines the corresponding traffic support level $I(t)$. The detailed decision sequence is illustrated in Figure 1. The platform charges the manufacturer a commission fee equal to $\varphi P(t)D_m(t)$. After paying the commission fee, the manufacturer retains sales revenue of $(1-\varphi)P(t)D_m(t)$ and bears the production cost $cD_m(t)$, the cost of quality improvement effort, and the cost of carbon emission reduction effort. Its instantaneous profit is therefore $[(1-\varphi)P(t) - c]D_m(t) - C_Q(t) - C_H(t)$. The platform receives the commission revenue and bears the cost of traffic support, giving an instantaneous profit of $\varphi P(t)D_m(t) - C_I(t)$. Both parties maximize their discounted profits while considering how their decisions affect future demand through green goodwill accumulation. The profit maximization problems of the manufacturer and the platform can therefore be formulated as follows:

$$\begin{aligned}
\max_{P,Q,H}\Pi_m^{TA} &= \int_0^\infty e^{-\rho t}\Big\{[(1-\varphi)P(t) - c]D_m(t) - C_Q(t) - C_H(t)\Big\}\,dt,\\
\max_{I}\Pi_e^{TA} &= \int_0^\infty e^{-\rho t}\Big(\varphi P(t)D_m(t) - C_I(t)\Big)\,dt,\\
\dot{G}(t) &= \tau Q(t) + \lambda H(t) + \varepsilon I(t) - \delta G(t), \quad G(0) = G^0.
\end{aligned} \tag{4.7}$$

In Case TA, Proposition 2 characterizes the feedback Stackelberg equilibrium strategies.

Proposition 2. *In Case TA, the unique feedback Stackelberg equilibrium strategies are given by*

$$P^{TA} = \frac{1}{2}\left(\frac{\alpha+\beta G}{\gamma} + \frac{c}{1-\varphi}\right), \tag{4.8}$$

$$I^{TA} = \frac{\varepsilon}{\mu}\left(L_1^{TA}G + L_2^{TA}\right), \tag{4.9}$$

$$Q^{TA} = \frac{\tau}{\xi}\left(K_1^{TA}G + K_2^{TA}\right), \tag{4.10}$$

$$H^{TA} = \frac{\lambda}{\eta}\left(K_1^{TA}G + K_2^{TA}\right). \tag{4.11}$$

The value functions of the manufacturer and the platform are, respectively, given by

$$J_m^{TA} = \frac{1}{2}K_1^{TA}G^2 + K_2^{TA}G + K_3^{TA},$$
$$J_e^{TA} = \frac{1}{2}L_1^{TA}G^2 + L_2^{TA}G + L_3^{TA},$$

where the coefficients K_j^{TA} and L_j^{TA} ($j = 1, 2, 3$) are derived in the proof. The equilibrium level of green goodwill is also obtained in the proof.

Proof. See Appendix B. □

Similar to Proposition 1, the value functions are quadratic functions, and the relationships between the strategies and the state variable are linear. It can be easily shown that the retail price increases monotonically with green goodwill, indicating that consumers are willing to pay a higher price for products with a higher level of green goodwill. In addition, since the coefficients associated with the manufacturer's carbon emission reduction effort, quality improvement effort, and the platform's traffic support level can only be obtained numerically, further analytical analysis cannot be derived.

5. Low-carbon model

In this section, we obtain the low-carbon model by excluding the platform's traffic support from the traffic support model. Accordingly, $I(t) = 0$, and the terms $\varepsilon I(t)$ and $C_I(t)$ are removed from the green goodwill dynamics and the platform's profit function, respectively. In this exogenously specified setting, the manufacturer operates outside the low-carbon zone and therefore receives no traffic support from the platform, while continuing to undertake both quality improvement and carbon emission reduction efforts. The cost functions of quality improvement effort and carbon emission reduction effort remain unchanged, and the manufacturer determines the levels of quality improvement effort and carbon emission reduction effort in each case. The low-carbon model therefore serves as a benchmark for examining the incremental effect of the platform's traffic support under the same sales mode. Excluding the platform's traffic support removes the corresponding decision and cost term and does not require setting the cost coefficient μ to zero. We focus on the reselling mode (Case LR) and the agency mode (Case LA) under the low-carbon model.

5.1. Case LR

For ease of exposition, the superscripts *LR* and *LA* denote the reselling mode and the agency mode under the low-carbon model, respectively, while the subscripts *m* and *e* represent the manufacturer and the platform, respectively. In Case LR, the manufacturer sells its products to the platform at the wholesale price $W(t)$. The manufacturer determines the wholesale price $W(t)$, the quality improvement effort $Q(t)$, and the carbon emission reduction effort $H(t)$. Given these decisions, the platform determines the retail price $P(t)$. Since no traffic support strategy is implemented, the platform does not incur any traffic support cost. The manufacturer's instantaneous profit is $[W(t)-c]D_e(t)-C_Q(t)-C_H(t)$, while the platform's instantaneous profit is $[P(t)-W(t)]D_e(t)$. Quality improvement effort and carbon emission reduction effort contribute to green goodwill accumulation and therefore affect the future profits of both parties. Accordingly, the profit maximization problems of the manufacturer and the platform are formulated as follows:

$$\begin{aligned}\max_{W,Q,H}\Pi_m^{LR} &= \int_0^\infty e^{-\rho t}\Big[(W(t)-c)D_e(t)-C_Q(t)-C_H(t)\Big]\,dt,\\ \max_{P}\Pi_e^{LR} &= \int_0^\infty e^{-\rho t}\Big[(P(t)-W(t))D_e(t)\Big]\,dt,\\ \dot{G}(t) &= \tau Q(t)+\lambda H(t)-\delta G(t), \qquad G(0)=G^0.\end{aligned} \tag{5.1}$$

Proposition 3. *In Case LR, the unique feedback Stackelberg equilibrium strategies are given by*

$$W^{LR}=\frac{\alpha+\beta G+\gamma c}{2\gamma}, \tag{5.2}$$

$$Q^{LR}=\frac{\tau}{\xi}\left(S_1^{TA}G+S_2^{TA}\right), \tag{5.3}$$

$$H^{LR}=\frac{\lambda}{\eta}\left(S_1^{TA}G+S_2^{TA}\right), \tag{5.4}$$

$$P^{LR}=\frac{3\alpha+3\beta G+\gamma c}{4\gamma}. \tag{5.5}$$

The value functions of the manufacturer and the platform are, respectively, given by

$$\begin{aligned}J_m^{LR}&=\frac{1}{2}S_1^{LR}G^2+S_2^{LR}G+S_3^{LR},\\ J_e^{LR}&=\frac{1}{2}Z_1^{LR}G^2+Z_2^{LR}G+Z_3^{LR}.\end{aligned}$$

where the coefficients S_j^{BR} and Z_j^{BR} ($j=1,2,3$) are derived in the proof. The equilibrium level of the manufacturer's goodwill is also obtained in the proof.

Proof. See Appendix C. □

5.2. Case LA

Under Case LA, the manufacturer sells its products directly to consumers through the platform marketplace. The manufacturer determines the retail price $P(t)$, the quality improvement effort $Q(t)$, and the carbon emission reduction effort $H(t)$. The platform does not provide traffic support and therefore does not determine a traffic support level or incur a traffic support cost. The platform charges the manufacturer a commission fee equal to $\varphi P(t)D_m(t)$, where φ denotes the commission rate. Hence, the manufacturer retains a fraction $1-\varphi$ of the sales revenue. The manufacturer's instantaneous profit is $[(1-\varphi)P(t)-c]D_m(t)-C_Q(t)-C_H(t)$, while the platform's instantaneous profit is $\varphi P(t)D_m(t)$. Since the commission rate is fixed and the platform does not provide traffic support, the platform has no decision variable in this case. Its value function is obtained from the future commission revenue under the manufacturer's equilibrium strategies. The manufacturer's profit maximization problem is therefore given by

$$\begin{aligned}\max_{P,Q,H}\Pi_m^{LA} &= \int_0^\infty e^{-\rho t}\Big[((1-\varphi)P(t)-c)D_m(t)-C_Q(t)-C_H(t)\Big]\,dt,\\ \dot{G}(t) &= \tau Q(t)+\lambda H(t)-\delta G(t), \qquad G(0)=G^0.\end{aligned} \tag{5.6}$$

Proposition 4. *In Case LA, the unique feedback Stackelberg equilibrium strategies are given by*

$$P^{LA}=\frac{1}{2}\left(\frac{\alpha+\beta G}{\gamma}+\frac{c}{1-\varphi}\right), \tag{5.7}$$

$$Q^{LA}=\frac{\tau}{\xi}\left(O_1^{TA}G+O_2^{TA}\right), \tag{5.8}$$

$$H^{LA}=\frac{\lambda}{\eta}\left(O_1^{TA}G+O_2^{TA}\right). \tag{5.9}$$

The value functions of the manufacturer and the platform are, respectively, given by

$$\begin{aligned}J_m^{LA}&=\frac{1}{2}O_1^{LA}G^2+O_2^{LA}G+O_3^{LA},\\ J_e^{LA}&=\frac{1}{2}B_1^{LA}G^2+B_2^{LA}G+B_3^{LA}.\end{aligned}$$

where the coefficients O_j^{BR} and B_j^{BR} ($j=1,2,3$) are derived in the proof. The equilibrium level of the manufacturer's goodwill is also obtained in the proof.

Proof. See Appendix D. □

6. Traditional model

In this section, we obtain the traditional model by excluding carbon emission reduction effort and platform traffic support from the traffic support model. Accordingly, $H(t)=I(t)=0$, and the corresponding terms are removed from the green goodwill dynamics and profit functions. In this exogenously specified setting, the manufacturer operates outside the low-carbon zone, receives no platform traffic support, and undertakes only quality improvement effort. The green goodwill dynamics become $\dot{G}(t)=\tau Q(t)-\delta G(t)$, and the cost function of quality improvement effort remains unchanged.

The comparison between the traditional model and the low-carbon model examines the effect of carbon emission reduction effort. The comparison between the traditional model and the traffic support model examines the combined effects of carbon emission reduction effort and the platform's traffic support. The separate effect of the platform's traffic support is examined by comparing the low-carbon model with the traffic support model. As in the low-carbon model, the corresponding activities and cost terms are removed without setting the cost coefficients η or μ to zero. We focus on the reselling mode (Case BR) and the agency mode (Case BA) under the traditional model.

6.1. Case BR

In Case BR, the manufacturer's sales revenue is $W(t)D_e(t)$, and the manufacturer bears the production cost $cD_e(t)$ and the cost of quality improvement effort $C_Q(t)$. Its instantaneous profit is therefore $[W(t) - c]D_e(t) - C_Q(t)$. The platform receives the sales revenue $P(t)D_e(t)$ and pays $W(t)D_e(t)$ to the manufacturer, giving an instantaneous profit of $[P(t) - W(t)]D_e(t)$. Quality improvement effort contributes to green goodwill accumulation, while existing green goodwill decays over time. Therefore, quality improvement effort affects the future profits of both parties through green goodwill. The cumulative discounted profits of the manufacturer and the platform over $t \in [0, +\infty)$ are given by

$$\begin{aligned} \max_{W,Q} \Pi_m^{BR} &= \int_0^\infty e^{-\rho t}\Big[(W(t) - c)D_e(t) - C_Q(t)\Big]dt, \\ \max_{P} \Pi_e^{BR} &= \int_0^\infty e^{-\rho t}\Big[(P(t) - W(t))D_e(t)\Big]dt, \\ \dot{G}(t) &= \tau Q(t) - \delta G(t), \quad G(0) = G^0. \end{aligned} \tag{6.1}$$

In Case BR, the equilibrium results are characterized in Proposition 3.

Proposition 5. *In Case BR, the unique feedback Stackelberg equilibrium strategies are given by*

$$P^{BR} = \frac{3\alpha + 3\beta G + \gamma c}{4\gamma}, \tag{6.2}$$

$$W^{BR} = \frac{\alpha + \beta G + \gamma c}{2\gamma}, \tag{6.3}$$

$$Q^{BR} = \frac{\tau}{\xi}\left(M_1^{BR} G + M_2^{BR}\right). \tag{6.4}$$

The value functions of the manufacturer and the platform are, respectively, given by

$$\begin{aligned} J_m^{BR} &= \frac{1}{2}M_1^{BR}G^2 + M_2^{BR}G + M_3^{BR}, \\ J_e^{BR} &= \frac{1}{2}N_1^{BR}G^2 + N_2^{BR}G + N_3^{BR}, \end{aligned}$$

where the coefficients M_j^{BR} and N_j^{BR} ($j = 1, 2, 3$) are derived in the proof. The equilibrium level of the manufacturer's goodwill is also obtained in the proof.

Proof. See Appendix E. □

6.2. Case BA

In Case BA, the manufacturer retains sales revenue of $(1-\varphi)P(t)D_m(t)$ after paying the commission fee and bears the production cost $cD_m(t)$ and the cost of quality improvement effort $C_Q(t)$. Its instantaneous profit is therefore $[(1-\varphi)P(t)-c]D_m(t)-C_Q(t)$. The platform's profit is solely derived from commission revenue. Since the commission rate is fixed and the platform does not provide traffic support, the platform has no decision variable in this case. The manufacturer determines the retail price and quality improvement effort, considering the effect of quality improvement effort on future demand through green goodwill accumulation. The platform's value function is obtained from the future commission revenue under the manufacturer's equilibrium strategies. The manufacturer's optimization problem is formulated as follows:

$$\begin{aligned} \max_{P,Q} \Pi_m^{BA} &= \int_0^\infty e^{-\rho t}\Big\{[(1-\varphi)P(t)-c]D_m(t)-C_Q(t)\Big\}\,dt, \\ \dot{G}(t) &= \tau Q(t)-\delta G(t), \quad G(0)=G^0. \end{aligned} \tag{6.5}$$

In Case BA, the equilibrium results are characterized in Proposition 4.

Proposition 6. *In Case BA, the unique feedback Stackelberg equilibrium strategies are given by*

$$P^{BA} = \frac{1}{2}\left(\frac{\alpha+\beta G}{\gamma}+\frac{c}{1-\varphi}\right), \tag{6.6}$$

$$Q^{BA} = \frac{\tau}{\xi}\left(X_1^{BA}G+X_2^{BA}\right). \tag{6.7}$$

The value functions of the manufacturer and the platform are, respectively, given by

$$\begin{aligned} J_m^{BA} &= \frac{1}{2}X_1^{BA}G^2+X_2^{BA}G+X_3^{BA}, \\ J_e^{BA} &= \frac{1}{2}Y_1^{BA}G^2+Y_2^{BA}G+Y_3^{BA}, \end{aligned}$$

where the coefficients X_j^{BA} and Y_j^{BA} ($j=1,2,3$) are derived in the proof. The equilibrium level of the manufacturer's goodwill is also obtained in the proof.

Proof. See Appendix F. □

7. Equilibrium comparisons and sales mode preferences

Let $k \in \{B, L, T\}$ denote the traditional, low-carbon, and traffic support models, and let $s \in \{R, A\}$ denote reselling and agency selling, respectively; write $j = ks$. Although the six cases share the same initial green goodwill $G^0 \geq 0$, each generates its own equilibrium trajectory $G^j(t)$. Write the value functions in Propositions 1–6 uniformly as

$$J_m^j(g) = \tfrac{1}{2}a_j g^2 + d_j g + k_j, \qquad J_e^j(g) = \tfrac{1}{2}b_j g^2 + e_j g + l_j.$$

where g is the level of green goodwill. The comparisons below are made at each case's own $G^j(t)$ or steady state $\bar{G}^j$; the corresponding coefficients are given in Appendix G.

7.1. Equilibrium comparisons

Corollary 1. *For the following corollary, let* $\bar{\kappa} = \frac{\tau^2}{\xi} + \frac{\lambda^2}{\eta}$, $\bar{\chi} = \frac{\varepsilon^2}{\mu}$, $\sigma = \rho + 2\delta$, $r_* = \min\{\delta, \sigma/4\}$, *and let*$(q_m^R, q_e^R) = \left(\frac{\beta^2}{4\gamma}, \frac{\beta^2}{8\gamma}\right)$,$(q_m^A, q_e^A) = \left(\frac{(1-\varphi)\beta^2}{2\gamma}, \frac{\varphi\beta^2}{2\gamma}\right)$. *If the model parameters satisfy* $\alpha > \frac{\gamma c}{1-\varphi}$, $\bar{\kappa} q_m^s + \bar{\chi} q_e^s < \sigma r_* - \frac{3}{2} r_*^2$, *where* $s \in \{R, A\}$, *then, for the non-negative, stable quadratic value-function solutions constructed in Appendix G.1, when the three models share the same initial green goodwill* $G^0 \geq 0$, *the following hold for any* $t \geq 0$*:*

$$\begin{aligned} G^{Ts}(t) &\geq G^{Ls}(t) \geq G^{Bs}(t), \\ Q^{Ts}(G^{Ts}(t)) &\geq Q^{Ls}(G^{Ls}(t)) \geq Q^{Bs}(G^{Bs}(t)), \\ H^{Ts}(G^{Ts}(t)) &\geq H^{Ls}(G^{Ls}(t)), \\ J_i^{Ts}(G^{Ts}(t)) &\geq J_i^{Ls}(G^{Ls}(t)) \geq J_i^{Bs}(G^{Bs}(t)), \quad i \in \{m, e\}. \end{aligned}$$

As $t \to \infty$, *the green goodwill in each model converges to its own steady state, and the above rankings of green goodwill, quality improvement effort, and carbon emission reduction effort, as well as the manufacturer's and platform's value functions, continue to hold. Let* $\bar{J}_i^j = J_i^j(\bar{G}^j)$ *denote the value function at the steady state, and let* $\bar{\pi}_i^j$ *denote the instantaneous profit at the steady state, where* $j \in \{Ts, Ls, Bs\}$. *Then*

$$\bar{\pi}_i^j = \rho \bar{J}_i^j, \qquad \bar{\pi}_i^{Ts} \geq \bar{\pi}_i^{Ls} \geq \bar{\pi}_i^{Bs}, \quad i \in \{m, e\}.$$

The proof is given in Appendix G.1. This corollary shows that, under the parameter conditions and within the range of equilibrium solutions specified in Appendix G.1, for a fixed sales mode, quality improvement effort and green goodwill in the traffic support model, as well as both parties' steady-state performance, are no lower than in the low-carbon model. Thus, when the manufacturer already undertakes carbon emission reduction, platform traffic support can further promote quality improvement and the accumulation of green goodwill without reducing either the manufacturer's or the platform's long-run steady-state payoff. Therefore, when the conditions above hold, the platform can use traffic support as a complementary measure to encourage the manufacturer to engage in low-carbon production, strengthen its incentive to invest, and account for both parties' long-run operating profits.

7.2. Sales mode choice

For a given operating model k, evaluate the manufacturer's and platform's long-run performance at the respective steady states under agency selling and reselling, and define $\Delta_i^{k,\infty} = J_i^{kA}(\bar{G}^{kA}) - J_i^{kR}(\bar{G}^{kR})$, $i \in \{m, e\}$. If $\Delta_i^{k,\infty} > 0$, member i prefers agency selling in terms of long-run performance; if $\Delta_i^{k,\infty} < 0$, it prefers reselling; if it equals zero, the member is indifferent between the two sales modes. Because the cases share the same positive discount rate and satisfy $\bar{\pi}_i^{ks} = \rho J_i^{ks}(\bar{G}^{ks})$, this comparison is equivalent to comparing instantaneous profits at the respective steady states. We next present the manufacturer's and platform's sales mode choices in the traditional and low-carbon models. Using the definition of κ_k above, let $C = \gamma c$, $v = \delta(\rho + \delta)$, $B_k = \frac{\kappa_k \beta^2}{2\gamma}$.

Corollary 2. *Suppose* $\alpha > C$, $B_k < v$, $k \in \{B, L\}$, *and* $0 < \varphi < \varphi_{\max}$, $\varphi_{\max} = 1 - \frac{C}{\alpha}$.

For the non-negative, stable quadratic value-function solutions identified in the appendix, the following conclusions hold.

(i) *The steady-state green goodwill levels under the two sales modes are, respectively*

$$\begin{aligned}\bar{G}^{kR} &= \frac{\kappa_k\beta(\alpha-\gamma c)}{4\gamma\delta(\rho+\delta)-\kappa_k\beta^2},\\ \bar{G}^{kA} &= \frac{\kappa_k\beta[(1-\varphi)\alpha-\gamma c]}{2\gamma\delta(\rho+\delta)-\kappa_k(1-\varphi)\beta^2}.\end{aligned} \tag{7.1}$$

There is a commission-rate threshold

$$\varphi_{G,k} = \frac{2\delta(\rho+\delta)(\alpha-\gamma c)}{4\delta(\rho+\delta)\alpha-\kappa_k\beta^2 c} \in (0,\varphi_{\max}). \tag{7.2}$$

If $\varphi < \varphi_{G,k}$, the manufacturer's steady-state green goodwill and quality improvement effort under agency selling are both higher than under reselling; otherwise, the reverse holds. For the low-carbon model $k = L$, the manufacturer's steady-state carbon emission reduction effort follows the same commission rate threshold and ranking. (ii) *If $\varphi < \varphi^{\infty}_{m,k}$, the manufacturer prefers agency selling in the long run; otherwise, it prefers reselling.*

(iii) *The platform's profit under agency selling exceeds that under reselling if and only if*

$$\varphi\left[\frac{(\alpha v - B_k C)^2}{[v-B_k(1-\varphi)]^2} - \frac{C^2}{(1-\varphi)^2}\right] > \frac{(\alpha-C)^2 v^2}{4(v-B_k/2)^2}. \tag{7.3}$$

If the above inequality is strictly reversed, the platform's profit is higher under reselling. When the commission rate is sufficiently close to the lower bound 0 *or the upper bound $\varphi_{\max}$ of the feasible interval, the platform's profit is higher under reselling.*

The proof is given in Appendix G.2. This corollary shows that, under the abovementioned parameter conditions, a higher commission rate reduces the manufacturer's long-run performance under agency selling and, once the relevant threshold is exceeded, leads it to prefer reselling. The platform must consider both the commission rate and its effects on demand and green goodwill when evaluating the long-run payoff under agency selling. Therefore, when setting its commission rate, the platform should consider both its own payoff and the manufacturer's incentive to invest, using the manufacturer's commission-rate threshold as an important reference for coordinating their sales mode choices. If their respective steady-state profits are used as the criterion, a commission rate under which both parties prefer agency selling must simultaneously be below the manufacturer's threshold and yield a higher steady-state profit for the platform under agency selling than under reselling. Only when both conditions hold can agency selling be the shared choice in terms of long-run performance.

7.3. Price comparisons

Substituting the respective green goodwill trajectories under agency selling and reselling into the equilibrium price expressions in Propositions 1–6 yields

$$P^{kR}(t) - P^{kA}(t) = \frac{\alpha + \beta[3G^{kR}(t) - 2G^{kA}(t)] - \gamma c(1+\varphi)/(1-\varphi)}{4\gamma}. \tag{7.4}$$

Here, $k \in \{B, L, T\}$, and $P^{ks}(t)$ denotes the retail price under the sales mode s along its own equilibrium trajectory $G^{ks}(t)$.

Corollary 3. *Provided that the interior equilibrium solutions of the cases being compared are feasible, suppose* $0 < \varphi < 1$ *and that the two sales modes share the same initial green goodwill* $G^0 \geq 0$. *Then the following conclusions hold.* (i) *At any given time* $t \geq 0$, *the retail price under reselling exceeds that under agency selling if and only if*$\alpha + \beta[3G^{kR}(t) - 2G^{kA}(t)] > \frac{\gamma c(1+\varphi)}{1-\varphi}$. (ii) *At the initial time, the retail price under reselling exceeds that under agency selling if and only if* $\varphi < \frac{\alpha+\beta G^0-\gamma c}{\alpha+\beta G^0+\gamma c}$. (iii) *If green goodwill under the two sales modes converges to the respective steady states* $\bar{G}^{kR}$ *and* $\bar{G}^{kA}$, *and the corresponding steady-state retail prices are denoted* $\bar{P}^{kR}$ *and* $\bar{P}^{kA}$, *then* $\bar{P}^{kR} > \bar{P}^{kA}$ *if and only if* $\alpha + \beta[3\bar{G}^{kR} - 2\bar{G}^{kA}] > \frac{\gamma c(1+\varphi)}{1-\varphi}$. *If any of the abovementioned inequalities is strictly reversed, the corresponding retail price under agency selling exceeds that under reselling.*

The proof is given in Appendix G.3. This corollary shows that the ranking of retail prices under the two sales modes depends on the model parameters and the green goodwill accumulated under each mode. The price ranking at the common initial level of green goodwill cannot be directly extended to other times or to the long-run steady states. Moreover, a higher retail price does not necessarily imply a higher profit for the manufacturer or platform. Therefore, when evaluating sales modes, the manufacturer and platform should consider changes in price and sales volume arising from the accumulation of green goodwill and compare actual payoffs in light of payoff allocation and effort costs. If a sales mode is selected early in the operating period and maintained thereafter, the assessment should be based on total discounted profit from the common initial level of green goodwill, rather than equating an initial price advantage with a payoff advantage over the entire operating period.

8. Numerical simulation

In this section, we conduct a numerical analysis of the platform supply chain-associated differential game model to further verify the theoretical results and reveal the dynamic characteristics of the decision variables under different sales modes. The analysis mainly consists of two parts. The first part comparatively examines the dynamic changes in the strategies, state variables, and profits of the manufacturer and the platform under the reselling mode and the agency mode. The second part presents a sensitivity analysis, focusing on the effects of parameter changes on the strategies, state variables, and profits of the manufacturer and the platform under different sales modes within the low-carbon zone with traffic support model. The initial parameter values are shown in Table 2.

Table 2. The initial parameters used in the numerical experiments.

ρ	δ	β	γ	α	c	η
0.1	0.1	0.3	1.0	5.0	1.0	0.8
μ	ξ	λ	ε	τ	G_0	φ
0.4	0.6	0.2	0.15	0.4	2	0.1

8.1. Comparison

In this subsection, on the basis of the parameter values reported in Table 2, we conduct numerical analyses of six operational cases: TR, TA, LR, LA, BR, and BA. We systematically compare the supply chain members' equilibrium decisions, the dynamic evolution of the manufacturer's green goodwill, and the payoffs of both parties. The equilibrium decisions considered include product prices, the manufacturer's quality improvement and carbon emission reduction efforts, and the platform's traffic support level. Specifically, comparisons between TR and LR and between TA and LA are used to examine the effects of the platform's traffic support; comparisons between LR and BR and between LA and BA are conducted to identify the effects of the manufacturer's carbon emission reduction effort; and comparisons between TR and TA, LR and LA, and BR and BA are used to investigate how the sales mode affects the supply chain's equilibrium outcomes.

Figure 3 illustrates the evolution of the manufacturer's quality improvement effort across the six operational cases. Under the specified parameter values, quality improvement effort is consistently higher in the agency mode than in the corresponding reselling mode. The platform's traffic support further increases quality improvement effort in both sales modes: Effort is higher in Case TA than in Case LA and higher in Case TR than in Case LR, whereas the differences between Cases LA and BA and between Cases LR and BR are small. Under the specified parameter values, an appliance manufacturer planning to improve products' durability can consider adopting the agency mode with the platform's traffic support, which provides stronger incentives for sustained quality investment. These results suggest that sales mode and traffic support have more pronounced effects on quality improvement, while introducing carbon emission reduction alone has a relatively small incremental effect in this numerical analysis.

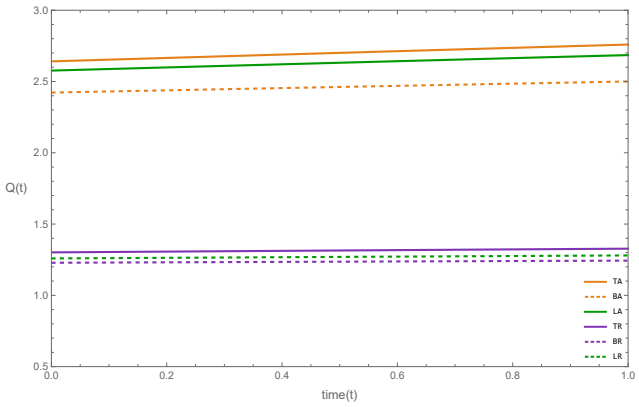
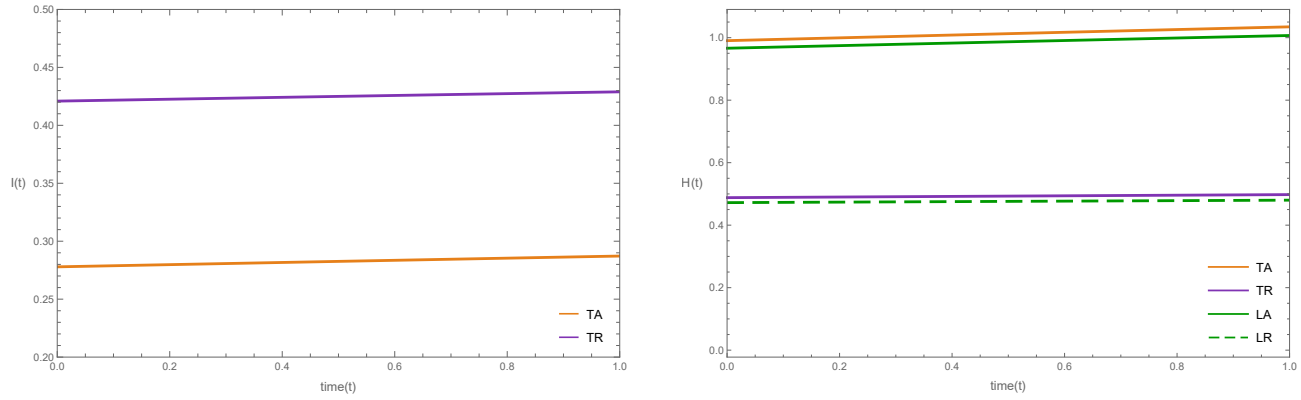


Figure 3. Quality improvement effort of the manufacturer in the six operational modes.

Figure 4 illustrates the evolution of the platform's traffic support level and the manufacturer's carbon emission reduction effort. Under the specified parameter values, Figure 4a shows that traffic support is consistently higher in Case TR than in Case TA. Under the specified parameter values, the platform has stronger incentives to provide traffic support under the reselling mode. For example, a platform purchasing refrigerators for resale can allocate recommendation slots in the low-carbon zone to enhance brand recognition, stimulate subsequent sales, and increase its future reselling profits. Figure 4b shows that carbon emission reduction effort is higher in the agency mode than in the corresponding reselling mode, both with and without traffic support. Moreover, carbon emission reduction effort is higher in

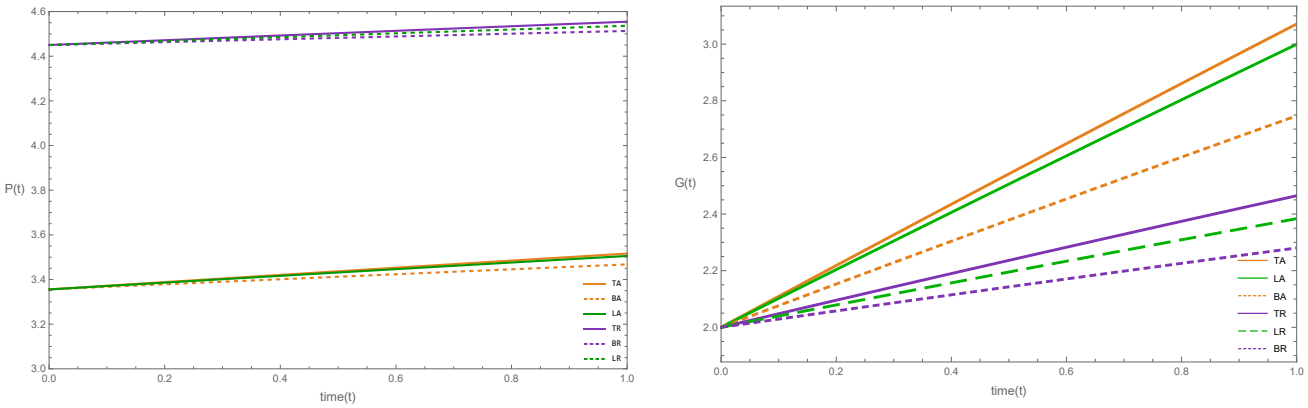
Case TA than in Case LA and higher in Case TR than in Case LR, suggesting that traffic support further strengthens the manufacturer's incentives for carbon emission reduction. Under the specified parameter values, a washing machine manufacturer, say, planning to increase its carbon emission reduction effort by improving production processes can consider adopting the agency mode with the platform's traffic support.



(a) The traffic support strategy of the e-commerce platform (b) Carbon emission reduction effort of the manufacturer.

Figure 4. Traffic support strategy of the e-commerce platform and carbon emission reduction effort of the manufacturer in the traffic support model.

These results indicate stronger incentives for platform traffic support under reselling and for manufacturer carbon emission reduction under agency selling.

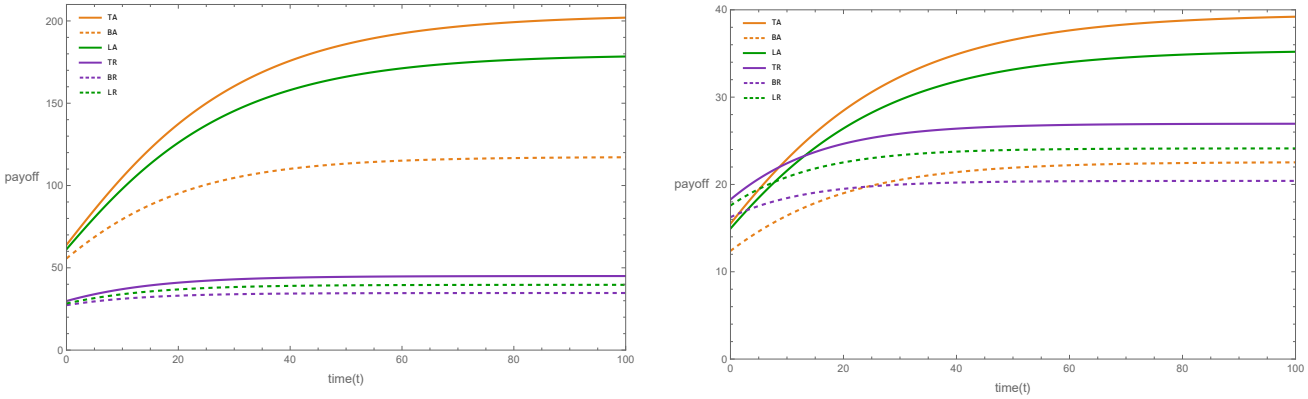


(a) Equilibrium price (b) Green goodwill

Figure 5. Equilibrium price and green goodwill in the six operational models.

Figure 5a,b illustrate the equilibrium retail price and the evolution of green goodwill across the six operational cases, respectively. Under the specified parameter values, retail prices are higher in the reselling mode than in the corresponding agency mode. For example, an appliance manufacturer launching a new refrigerator can consider adopting the agency mode to set the retail price directly and attract consumers with a lower price. As time progresses, the agency mode generates higher green goodwill than the corresponding reselling mode. Green goodwill is higher in Case TA than in Case

LA and higher in Case LA than in Case BA, with the same ordering observed across Cases TR, LR, and BR. These results suggest that both traffic support and carbon emission reduction contribute to goodwill accumulation. Together with Figures 3 and 4, they indicate that the manufacturer's greater quality improvement and carbon emission reduction efforts under agency selling more than offset the platform's lower traffic support, resulting in higher green goodwill. Manufacturers should therefore consider their quality improvement and carbon emission reduction plans alongside platform traffic support when choosing a sales mode. For example, an appliance manufacturer can improve refrigerators' durability and reduce carbon emissions from production to strengthen consumers' recognition of the brand.



(a) The evolution of manufacturer payoffs

(b) The evolution of e-commerce platform payoffs

Figure 6. The evolution of manufacturer and e-commerce platform payoffs over time in the six operational models.

Figure 6 compares the manufacturer's and the platform's payoff values along the equilibrium paths across the six operational cases. Each point represents the present value of future equilibrium profits, discounted to the current time t and conditional on the green goodwill level at that time. For example, in Case TR, the manufacturer's and the platform's payoff values are given by

$$J_m^{TR}(G^{TR}(t)) = \int_t^{\infty} e^{-\rho(s-t)}\Big[(W^{TR}(s)-c)(\alpha+\beta G^{TR}(s)-\gamma P^{TR}(s)) - \frac{\xi[Q^{TR}(s)]^2}{2} - \frac{\eta[H^{TR}(s)]^2}{2}\Big]ds, \tag{8.1}$$

and

$$J_e^{TR}(G^{TR}(t)) = \int_t^{\infty} e^{-\rho(s-t)}\Big[(P^{TR}(s)-W^{TR}(s))(\alpha+\beta G^{TR}(s)-\gamma P^{TR}(s)) - \frac{\mu[I^{TR}(s)]^2}{2}\Big]ds, \tag{8.2}$$

where all prices and effort levels are evaluated under the equilibrium strategies in Case TR. As green goodwill approaches its steady state, the corresponding payoff values also converge to steady-state levels.

Figure 6a shows that, under the specified parameter values, the manufacturer's payoff value is higher in the agency mode than in the corresponding reselling mode: Cases TA, LA, and BA yield higher

values than Cases TR, LR, and BR, respectively. Moreover, the manufacturer's payoff value is higher in Case TA than in Case LA and higher in Case TR than in Case LR, suggesting that the platform's traffic support increases the manufacturer's future discounted profits. However, the payoff curves for Cases LA and BA and for Cases LR and BR nearly coincide, suggesting a small incremental effect of introducing carbon emission reduction alone under the current numerical setting. These findings suggest that manufacturers can consider the agency mode with the platform's traffic support to improve discounted profits. For example, an appliance manufacturer launching a new refrigerator can assess this option by comparing the expected revenues and costs of both sales modes over the operating horizon.

Figure 6b shows that with traffic support, the platform's payoff value is initially higher in Case TR than in Case TA, but Case TA subsequently overtakes Case TR as green goodwill accumulates. A similar crossover occurs between Cases LR and LA, where carbon emission reduction is considered without traffic support: Case LR yields a higher platform payoff value initially, whereas Case LA yields a higher value at later stages. By contrast, in the benchmark setting with quality improvement alone, the platform's payoff value remains higher in Case BR than in Case BA. This difference suggests that introducing carbon emission reduction may alter the platform's sales mode preference. Together with Figures 3–5, these results indicate that the manufacturer's greater quality improvement and carbon emission reduction efforts under agency selling promote goodwill accumulation, thereby increasing the platform's future commission revenue. Furthermore, the platform's payoff value is higher in Case TA than in Case LA and higher in Case TR than in Case LR, suggesting that traffic support improves the platform's payoff value in both sales modes. The crossovers reflect changes in the ranking of future discounted profits rather than current-period profits. Therefore, platforms should compare discounted profits over the entire operating horizon when initially choosing a sales mode. For example, a platform introducing an appliance brand should evaluate both modes from the same initial level of green goodwill, since the subsequent payoff crossover does not establish which mode is preferable at entry.

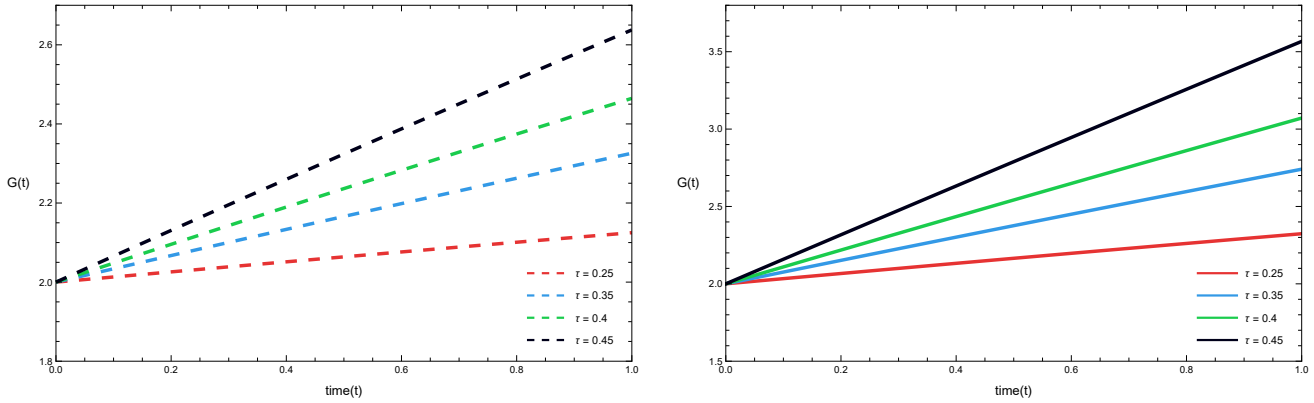
8.2. Sensitivity analysis

This subsection presents a sensitivity analysis of the traffic support model, examining how parameter changes affect the evolution of the manufacturer's green goodwill, carbon emission reduction effort, and quality improvement effort, as well as the payoff values of both the manufacturer and the platform under different sales modes.

Figure 7a,b illustrate the impact of the coefficient τ of product quality improvement effort on the manufacturer's green goodwill under the reselling mode and the agency mode, respectively. Both figures clearly show that the manufacturer's green goodwill increases monotonically as the coefficient τ increases. This phenomenon reveals the moderating role of τ in the accumulation of green goodwill: When other parameters remain unchanged, a higher value of τ means that the incremental green goodwill generated by the manufacturer's unit quality improvement effort is greater, indicating that the efficiency of converting quality improvement efforts into goodwill is higher. Therefore, under both sales modes, manufacturers should consider whether consumers recognize their quality improvements. For example, a refrigerator manufacturer can present durability test results to explain improvements in product quality, helping quality improvement efforts contribute more effectively to green goodwill.

Figure 8a,b illustrate the impact of the coefficient λ of the manufacturer's carbon emission reduction effort on the manufacturer's green goodwill under the reselling mode and the agency mode, respectively. As shown in the figures, green goodwill increases monotonically with λ in both modes. This result

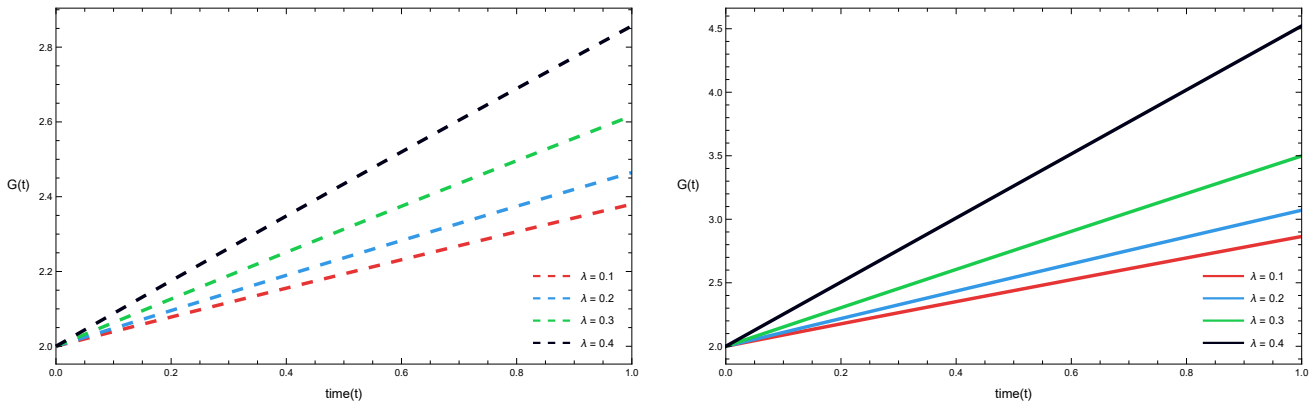
indicates the positive moderating role of λ in the formation of green goodwill: When other parameters remain unchanged, a higher value of λ leads to a more significant impact of unit carbon emission reduction effort on green goodwill, suggesting that the efficiency of converting carbon emission reduction efforts into green goodwill increases. Therefore, under both sales modes, manufacturers should help consumers recognize their carbon emission reduction efforts. For example, an appliance manufacturer can display verified information about reductions in carbon emissions from production on product pages, making these efforts more visible to consumers and supporting green goodwill accumulation.



(a) Impact of the variable τ on green goodwill in the reselling mode

(b) Impact of the variable τ on green goodwill in the agency mode

Figure 7. Impact of the variable τ on green goodwill.



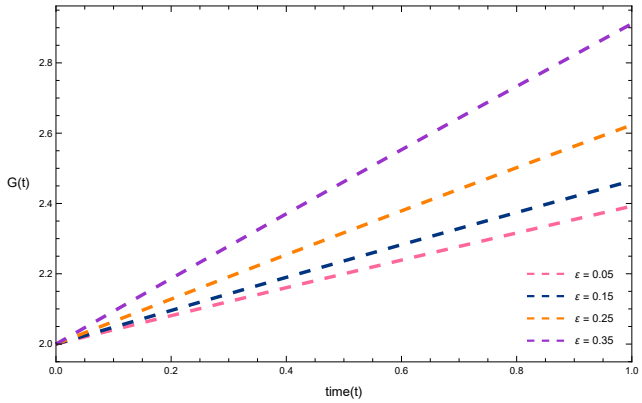
(a) Impact of the variable λ on green goodwill in the reselling mode

(b) Impact of the variable λ on green goodwill in the agency mode

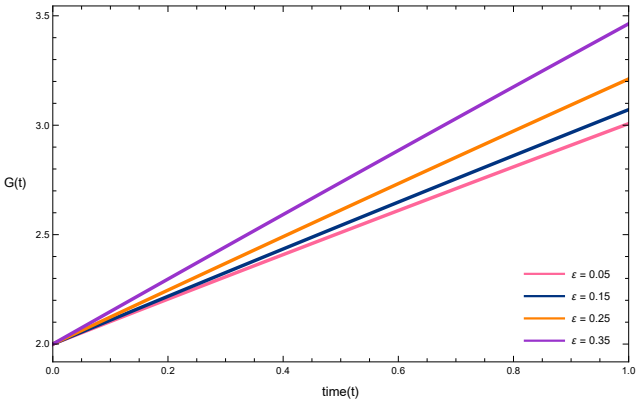
Figure 8. Impact of the variable λ on green goodwill.

Figure 9a,b illustrate the impact of the coefficient ε of the platform's traffic support on the manufacturer's green goodwill under the reselling mode and the agency mode, respectively. The results show that, in both modes, green goodwill increases monotonically as ε increases. Therefore, platforms should consider how effectively traffic support builds green goodwill under both sales modes. For example, an appliance platform can assess whether different recommendation placements in the

low-carbon zone strengthen consumers' recognition of the manufacturer's brand and support subsequent sales when allocating traffic resources.

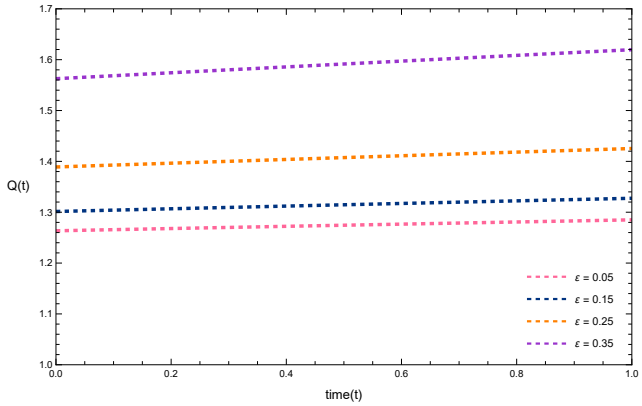


(a) Impact of the variable ε on green goodwill in the reselling mode

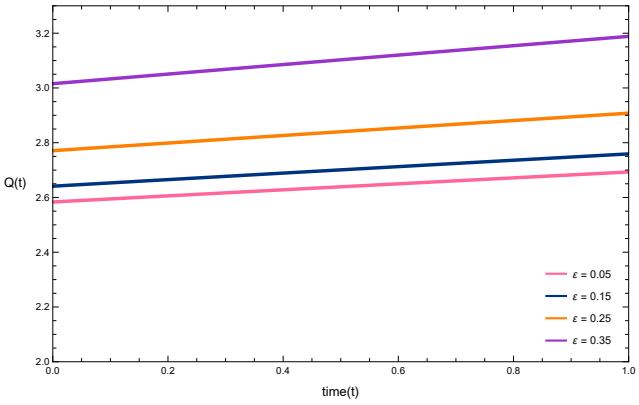


(b) Impact of the variable ε on green goodwill in the agency mode

Figure 9. Impact of the variable ε on green goodwill.



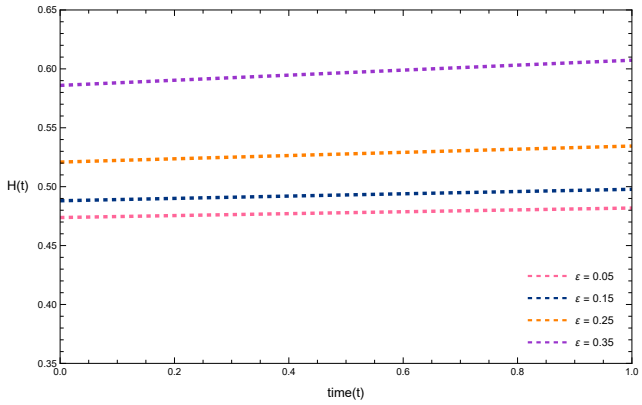
(a) Impact of the variable ε on quality improvement efforts in the reselling mode



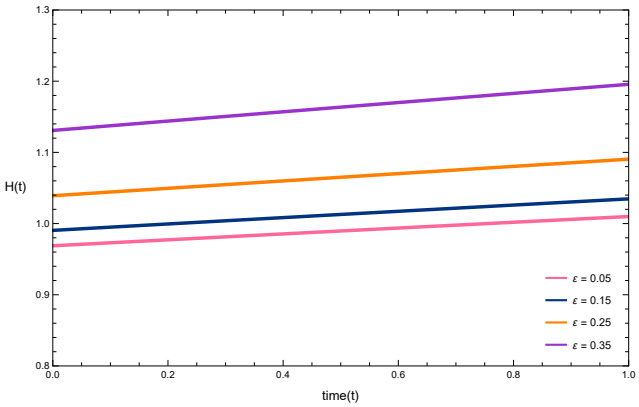
(b) Impact of the variable ε on quality improvement efforts in the agency mode

Figure 10. Impact of the variable ε on quality improvement efforts.

Figure 10 shows that quality improvement effort increases with ε in both sales modes under the parameter settings considered. Here, ε measures the effect of the platform's traffic support on green goodwill. The result indicates that greater effectiveness of traffic support in generating goodwill strengthens the manufacturer's incentives for quality improvement. Therefore, manufacturers should consider how effectively the platform's traffic support builds green goodwill when planning quality investment. For example, a refrigerator manufacturer planning durability upgrades can assess the expected returns on these investments in light of the goodwill generated by recommendations in the low-carbon zone.

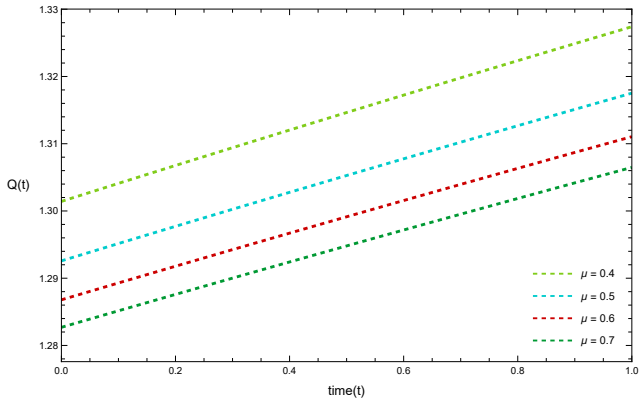


(a) Impact of the variable ε on carbon emission reduction efforts in the reselling mode

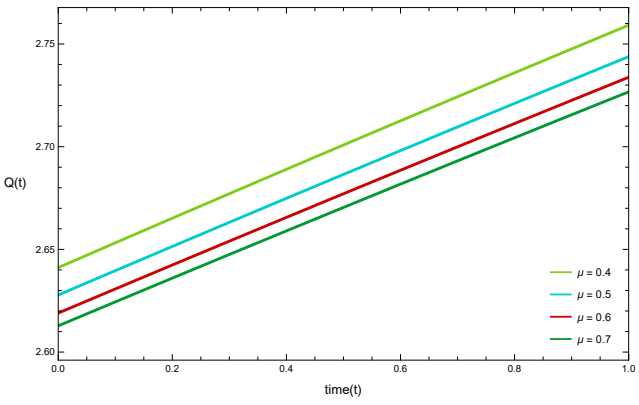


(b) Impact of the variable ε on carbon emission reduction efforts in the agency mode

Figure 11. Impact of the variable ε on carbon emission reduction efforts.



(a) Impact of the variable μ on quality improvement efforts in the reselling mode



(b) Impact of the variable μ on quality improvement efforts in the agency mode

Figure 12. Impact of the variable μ on quality improvement efforts.

Figure 11 illustrates the effect of ε, the effect coefficient of the platform's traffic support on green goodwill, on the manufacturer's carbon emission reduction effort. Under the parameter settings considered, a higher ε increases this effort in both sales modes, indicating that a more effective contribution of traffic support to goodwill accumulation strengthens the manufacturer's emission reduction incentives. Therefore, manufacturers should consider the goodwill effects of the platform's

traffic support when evaluating carbon emission reduction investments. For example, an appliance manufacturer planning to reduce carbon emissions through production process improvements can assess expected investment returns in light of how effectively recommendations in the low-carbon zone build green goodwill.

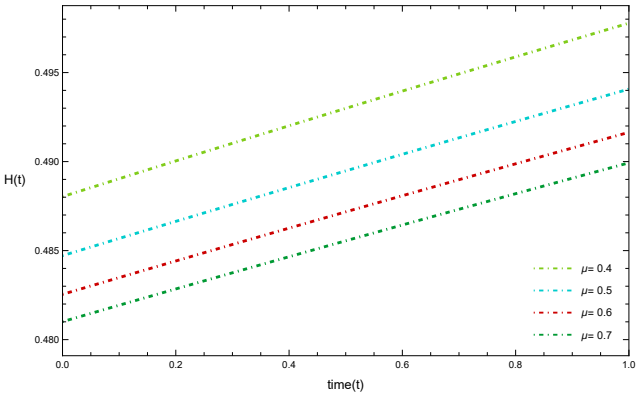
Figure 12a,b illustrates the impact of the platform's traffic support cost coefficient μ on the manufacturer's quality improvement effort under the two sales modes. As shown in the figures, an increase in μ suppresses the manufacturer's quality improvement effort, indicating a negative correlation between the two. This suggests that the higher the platform's traffic support cost, the lower the manufacturer's incentive to invest in quality improvement. Therefore, under both sales modes, platforms should consider the manufacturers' quality investment when responding to higher traffic support costs. For example, an appliance platform adjusting their recommendation placements for refrigerators in the low-carbon zone should assess how changes in traffic support may affect the manufacturer's planned investment in product durability.

Figure 13a,b illustrates the impact of the platform's traffic support cost coefficient μ on the manufacturer's carbon emission reduction effort under the two sales modes. As shown in the figures, an increase in μ suppresses the manufacturer's carbon emission reduction effort, indicating a negative correlation between the two. This suggests that higher platform traffic support costs reduce the manufacturer's willingness to invest in carbon emission reduction. Therefore, under both sales modes, manufacturers should consider the platform's traffic support costs when planning carbon emission reduction investment. For example, a refrigerator manufacturer planning to reduce carbon emissions through improving the production process can assess whether the investment remains financially attractive when the platform faces higher traffic support costs.

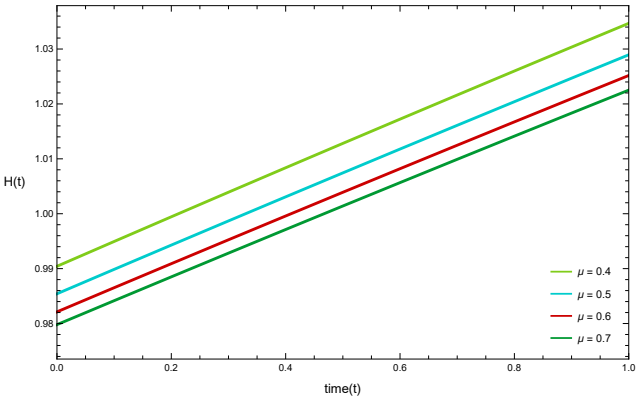
Figure 14a,b illustrates the impact of the platform's traffic support coefficient ε on the manufacturer's profit under the reselling mode and the agency mode, respectively. The results in both figures indicate that the manufacturer's profit increases monotonically as the coefficient ε increases. Therefore, manufacturers should evaluate the platform's traffic support by its contribution to future discounted profits under both sales modes. For example, a refrigerator manufacturer can compare recommendation arrangements in the low-carbon zone by their expected effects on green goodwill and subsequent sales, accounting for the costs it bears.

Figure 15a,b illustrates the impact of the platform's traffic support coefficient ε on its profit under the reselling mode and the agency mode, respectively. The results in both figures indicate that the platform's profit increases monotonically as the coefficient ε increases. Therefore, platforms should evaluate traffic support through its expected discounted returns. For example, an appliance platform allocating recommendation slots in the low-carbon zone can compare the expected increase in retail margins under reselling or commission revenue under agency selling with the associated traffic support costs.

Figure 16a,b illustrates the impact of the coefficient τ of the manufacturer's quality improvement effort on its profit under the reselling mode and the agency mode, respectively. The results in both figures indicate that the manufacturer's profit increases monotonically as the coefficient τ increases. Therefore, manufacturers should assess quality improvement projects by their costs and effectiveness in building green goodwill. For example, a refrigerator manufacturer comparing durability upgrades can consider consumers' recognition of the improvements and expected sales returns when selecting projects that improve discounted profits.

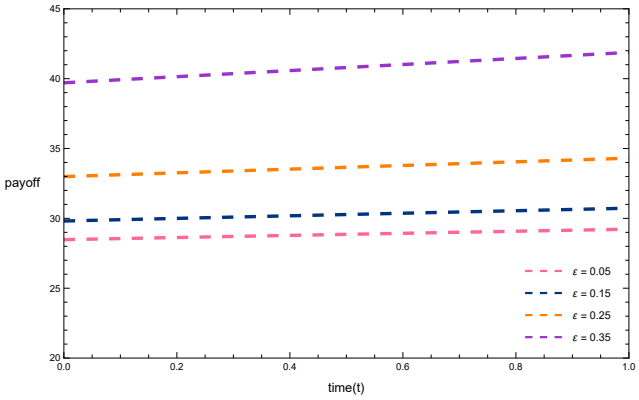


(a) Impact of the variable μ on carbon emission reduction efforts in the reselling mode

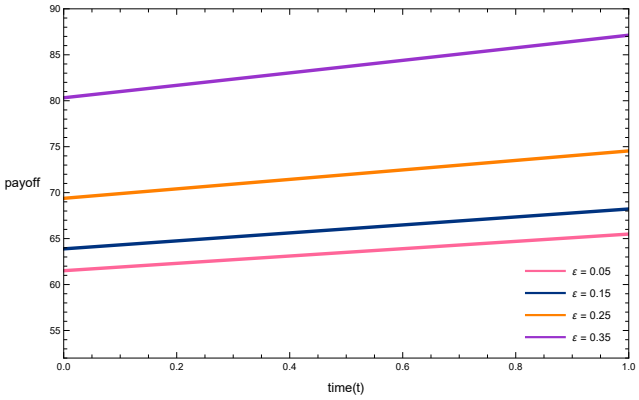


(b) Impact of the variable μ on carbon emission reduction efforts in the agency mode

Figure 13. Impact of the variable μ on carbon emission reduction efforts.

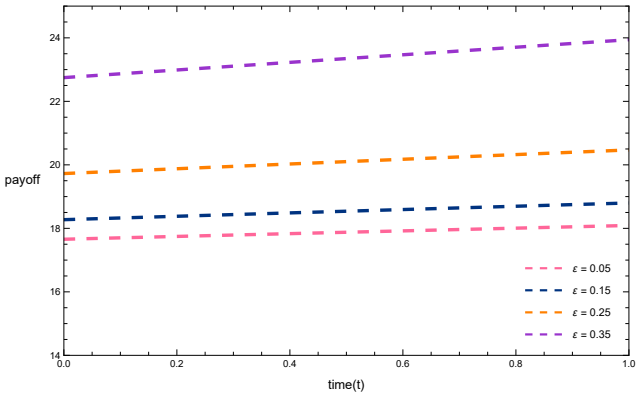


(a) Impact of the variable ε on the manufacturer's payoffs in the reselling mode

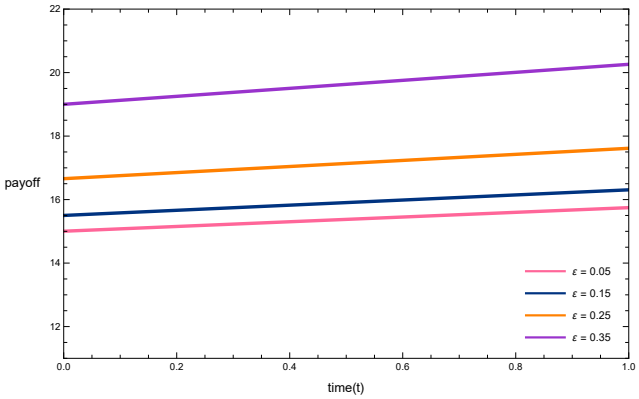


(b) Impact of the variable ε on the manufacturer's payoffs in the agency mode

Figure 14. Impact of the variable ε on the manufacturer's payoffs.

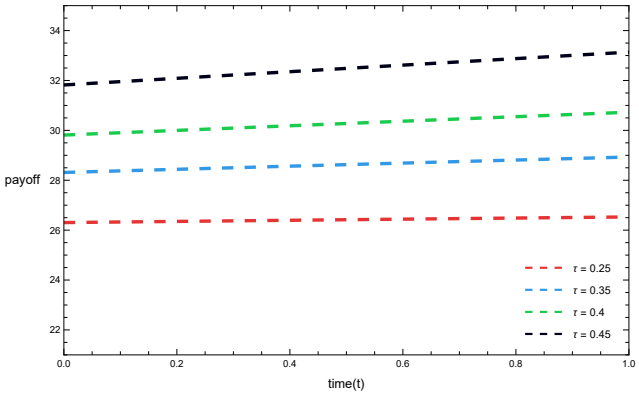


(a) Impact of the variable ε on the e-commerce platform's payoffs in the reselling mode

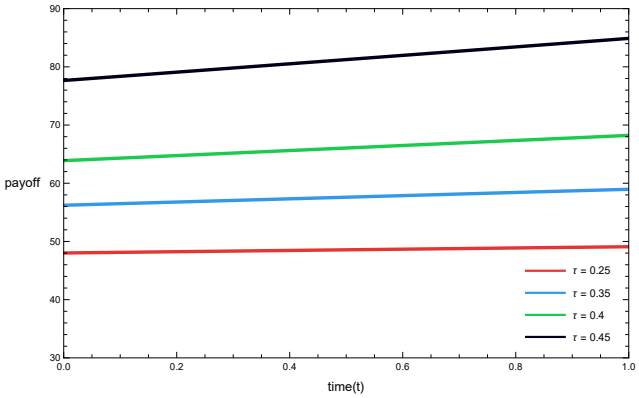


(b) Impact of the variable ε on the e-commerce platform's payoffs in the agency mode

Figure 15. Impact of the variable ε on the e-commerce platform's payoffs.



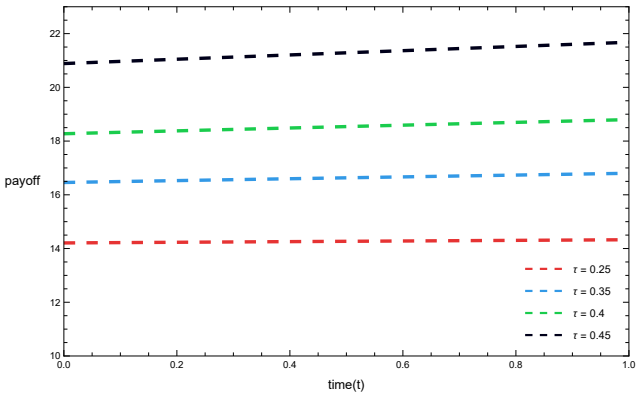
(a) Impact of the variable τ on the manufacturer's payoffs in the reselling mode



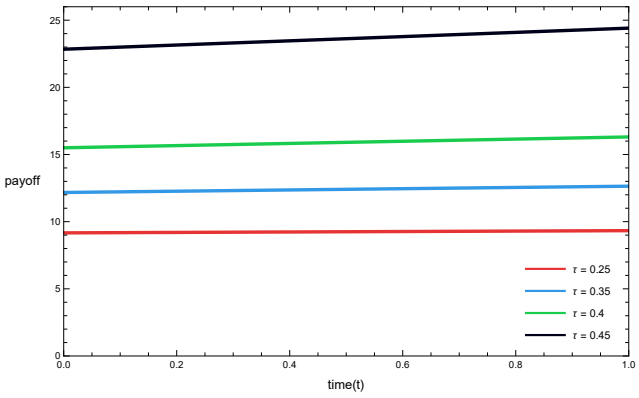
(b) Impact of the variable τ on the manufacturer's payoffs in the agency mode

Figure 16. Impact of the variable τ on the manufacturer's payoffs.

Figure 17a,b illustrates the impact of the coefficient τ of the manufacturer's quality improvement effort on the platform's profit under the reselling mode and the agency mode, respectively. The results in both figures indicate that the platform's profit increases monotonically as the coefficient τ increases. Therefore, platforms have an incentive to help consumers recognize the manufacturers' quality improvements. For example, an appliance platform can display verified refrigerator durability test results on their product pages, supporting green goodwill accumulation and future retail margins under reselling or commission revenues under agency selling.



(a) Impact of the variable τ on the e-commerce platform's payoffs in the reselling mode

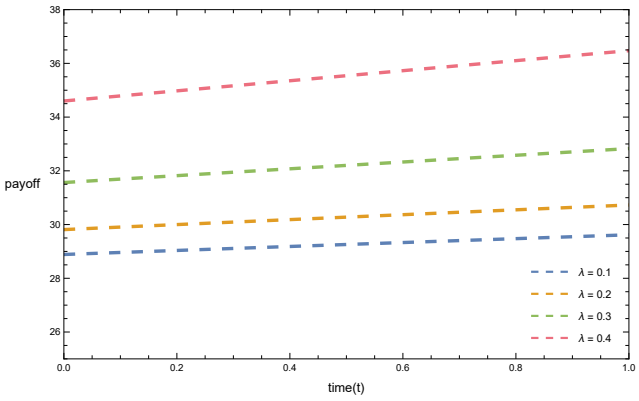


(b) Impact of the variable τ on the e-commerce platform's payoffs in the agency mode

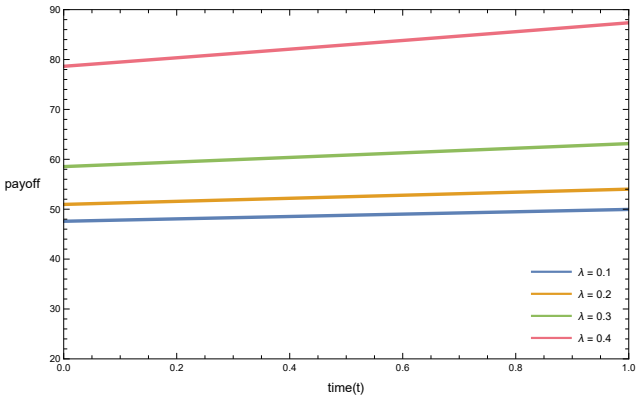
Figure 17. Impact of the variable τ on the e-commerce platform's payoffs.

Figure 18a,b illustrates the impact of the coefficient λ of the manufacturer's carbon emission reduction effort on its profit under the reselling mode and the agency mode, respectively. The results in both figures indicate that the manufacturer's profit increases monotonically as the coefficient λ increases. Therefore, manufacturers should consider how effectively their carbon emission reduction effort builds green goodwill when evaluating investment returns. For example, a refrigerator manufacturer can disclose verified reductions in carbon emissions from production on their product pages and assess the

expected sales revenue alongside the costs it bears under each sales mode.

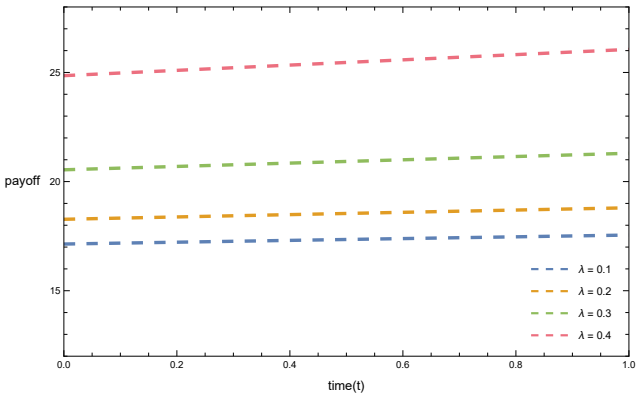


(a) Impact of the variable λ on the manufacturer's payoffs in the reselling mode

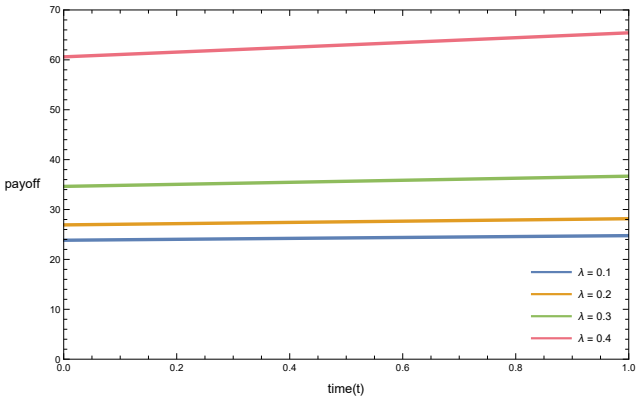


(b) Impact of the variable λ on the manufacturer's payoffs in the agency mode

Figure 18. Impact of the variable λ on the manufacturer's payoffs.



(a) Impact of the variable λ on the e-commerce platform's payoffs in the reselling mode



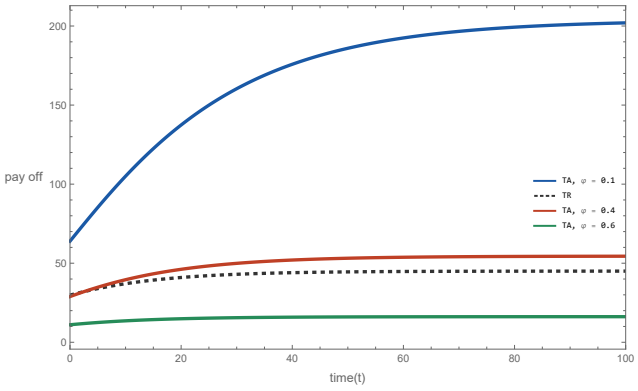
(b) Impact of the variable λ on the e-commerce platform's payoffs in the agency mode

Figure 19. Impact of the variable λ on the e-commerce platform's payoffs.

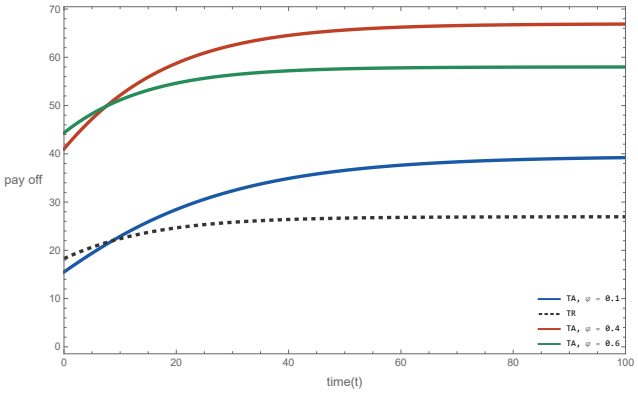
Figure 19a,b illustrates the impact of the coefficient λ of the manufacturer's carbon emission reduction effort on the platform's profit under the reselling mode and the agency mode, respectively. The results in both figures indicate that the platform's profit increases monotonically as the coefficient λ increases. Therefore, platforms have an incentive to help consumers recognize the manufacturers' carbon emission reduction efforts. For example, an appliance platform can display verified carbon emission reduction information in the low-carbon zone, helping build green goodwill and generate future retail margins under reselling or commission revenues under agency selling.

Figure 20a,b shows how changes in the commission rate φ affect the manufacturer's and platform's payoffs under reselling and agency selling, respectively. The results show that a higher platform commission rate reduces the manufacturer's payoff value under agency selling, but the platform's payoff does not increase monotonically with the commission rate. A higher commission rate raises the platform's share of revenue but also weakens the manufacturer's incentive to invest, thereby affecting

goodwill and demand. In particular, the platform's long-run steady-state payoff value is higher at $\varphi = 0.4$ than at $\varphi = 0.6$, whereas the ranking is reversed initially. This suggests that when setting the commission rate, the platform should consider both revenue sharing and the manufacturer's incentive to invest continuously, and assess the rate using long-run steady-state payoffs. For example, when introducing an appliance manufacturer into a low-carbon zone, the platform can use a moderate commission rate to sustain the manufacturer's incentive to improve product quality and undertake energy-saving production upgrades, thereby supporting green goodwill accumulation and higher long-run platform payoffs.

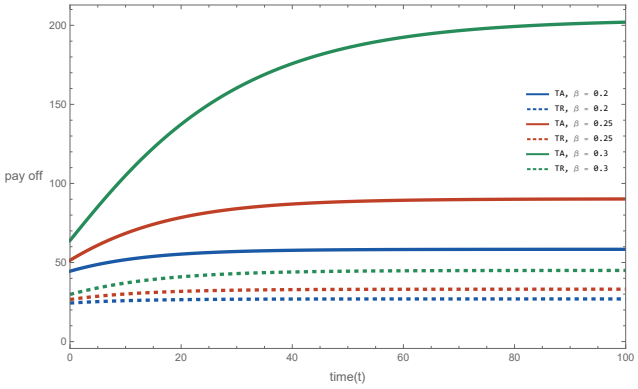


(a) Impact of the variable φ on the manufacturer's payoffs

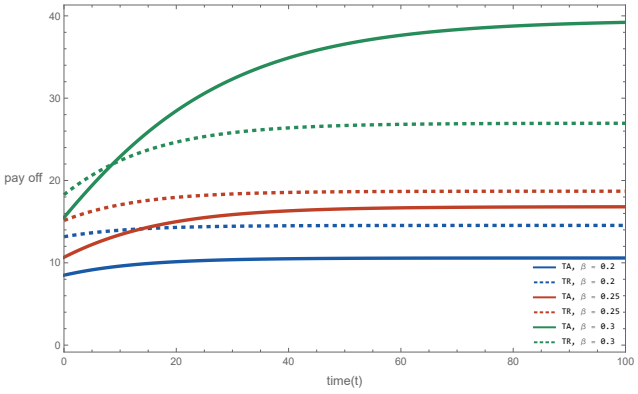


(b) Impact of the variable φ on the e-commerce platform's payoffs.

Figure 20. Effects of changes in the commission rate φ on the manufacturer's and the platform's profits.



(a) Impact of the variable β on the manufacturer's payoffs



(b) Impact of the variable β on the e-commerce platform's payoffs.

Figure 21. Effects of changes in the goodwill sensitivity coefficient β on the manufacturer's and the platform's profits.

Figure 21a, b shows how changes in goodwill sensitivity β affect the manufacturer's and platform's payoffs under reselling and agency selling, respectively. The results show that a higher β increases both parties' payoff values under both modes, although the magnitudes of the increases differ. At $\varphi = 0.1$, the platform prefers reselling in the long run when $\beta = 0.20$ or 0.25, but has a higher steady-

state payoff value under agency selling when $\beta = 0.30$. This indicates that, as goodwill translates more readily into demand, the advantage of agency selling in accumulating goodwill may change the platform's mode preference. Therefore, when evaluating the long-run payoffs of the two sales modes, the platform should consider how sensitive its target consumers are to green goodwill. For example, in an appliance market segment where the consumers' purchasing decisions are more strongly influenced by the product's quality reputation and an image of green manufacturing, the platform can focus on the goodwill accumulation benefits of agency selling and assess its long-run advantage in light of the specific commission rate and cost conditions.

8.3. Parameter robustness analysis

This subsection further varies the parameters to examine how changes in efforts, goodwill, and payoff values depend on the parameter values. The parameters examined include the commission rate, goodwill sensitivity coefficient, unit production cost, discount rate, and goodwill decay rate. Only one parameter is varied at a time; the others take their corresponding values from Table 2. Table 3 summarizes the calculated results for the two sales modes over the common feasible steady-state range to assess whether the corresponding patterns remain consistent over the listed parameter intervals.

Table 3. Effects of parameter changes on carbon emission reduction effort, traffic support, green goodwill, and payoff values.

Parameter and range	Manufacturer: H, J_m	Platform: I, J_e	Goodwill: G
$\varphi \in [0.02, 0.79]$	TA: H and J_m both decrease; TR: Both remain unchanged	TA: I increases, while J_e first increases and then decreases; TR: Both remain unchanged	TA: Decreases; TR: Remains unchanged
$\beta \in [0.15, 0.36]$	Both TA and TR increase	Both TA and TR increase	Both TA and TR increase
$c \in [0.50, 1.50]$	Both TA and TR decrease	Both TA and TR decrease	Both TA and TR decrease
$\rho \in [0.05, 0.20]$	Both TA and TR decrease	Both TA and TR decrease	Both TA and TR decrease
$\delta \in [0.08, 0.20]$	Both TA and TR decrease	Both TA and TR decrease	Both TA and TR decrease

Note: Only one parameter is varied at a time; the others take their corresponding values from Table 2. The parameter ranges shown are the common intervals over which both Case TA and Case TR satisfy the stability, positive demand, and effort feasibility conditions in these numerical calculations. H, I, and G denote the steady-state levels under the respective modes, and J_m and J_e are the manufacturer's and platform's payoff values at those steady states.

Table 3 summarizes the effects of the commission rate, goodwill sensitivity coefficient, unit production cost, discount rate, and goodwill decay rate on the manufacturer's carbon emission reduction effort, the platform's traffic support, green goodwill, and both parties' payoff values under agency selling and reselling. Only one parameter is varied at a time; the others take their corresponding values from Table 2. Over the common feasible steady-state ranges listed in Table 3, carbon emission

reduction effort, traffic support, green goodwill, and both parties' payoff values all rise with the goodwill sensitivity coefficient and fall with the unit production cost, the discount rate, and the goodwill decay rate. The commission rate does not affect these measures under reselling. Under agency selling, a higher commission rate reduces the manufacturer's carbon emission reduction effort and payoff value as well as green goodwill, increases the platform's traffic support, and causes the platform's payoff value to first rise and then fall, reflecting a trade-off between revenue sharing and incentives to invest. These results suggest that when assessing long-run investment, the manufacturer and platform should consider how effectively goodwill translates into demand, how persistent goodwill is, and how future payoffs are discounted. Because $Q = (\eta\tau)/(\lambda\xi)H$, and none of the five parameters changes this proportional relationship, quality improvement effort and carbon emission reduction effort move in the same direction; the former is therefore not listed separately.

9. Extended model

This section uses the reselling case TR and the agency case TA in the traffic support model as benchmarks. In both cases of the traffic support model, quality improvement effort Q and carbon emission reduction effort H contribute to the accumulation of the manufacturer's green goodwill, and their ratio satisfies $\frac{H}{Q} = \frac{\lambda\xi}{\eta\tau}$. Thus, when the coefficient τ of the effect of quality improvement effort on green goodwill, the coefficient λ of the effect of carbon emission reduction effort on green goodwill, and the corresponding cost coefficients ξ and η are fixed, the ratio of the two efforts remains unchanged. To further examine how the manufacturer adjusts its relative investment in quality improvement and carbon emission reduction, this section extends Cases TR and TA to account for the current-period demand response to information disclosed in the low-carbon zone. Experimental studies have shown that carbon footprint information and the way it is presented can affect consumers' choices, and that carbon labels in online shopping can also change consumers' product choices [50,51]. According to these studies, we assume that the platform can display verifiable information about the manufacturer's emission reduction activities to consumers. Consumers can then adjust their willingness to purchase in response to currently disclosed emission reduction information while evaluating the product on the basis of existing green goodwill. Consequently, in addition to affecting demand through goodwill, carbon emission reduction effort may generate an additional current-period demand return, thereby changing the manufacturer's relative incentives to invest in the two efforts. To represent this mechanism, we extend the demand functions for TR and TA as follows:

$$D^{\theta}(P, G, H) = \alpha + \beta G + \theta H - \gamma P, \qquad \theta \geq 0. \tag{9.1}$$

Here, $\theta \geq 0$ is the coefficient measuring the direct effect of carbon emission reduction effort on current-period demand under the given conditions of green information disclosure. Specifically, holding current green goodwill G and the retail price P fixed, each unit of increase in the manufacturer's carbon emission reduction effort adds θ to current-period demand through the disclosed verifiable information. The manufacturer's green goodwill dynamics remain

$$\dot{G} = \tau Q + \lambda H + \varepsilon I - \delta G, \qquad G(0) = G^0 \geq 0. \tag{9.2}$$

Here, Q and H continue to denote the manufacturer's quality improvement and carbon emission reduction efforts, respectively, and I remains the platform's traffic support level. Their respective costs

remain $\frac{\xi Q^2}{2}$, $\frac{\eta H^2}{2}$, and $\frac{\mu I^2}{2}$. The extended cases are denoted TR,θ and TA,θ, respectively; when $\theta = 0$, they reduce to Cases TR and TA.

Proposition 7. *In Case TR,θ, the unique feedback Stackelberg equilibrium strategies are given by*

$$\begin{aligned} W^{TR,\theta} &= \frac{\alpha+\beta G+\theta H^{TR,\theta}+\gamma c}{2\gamma},\\ P^{TR,\theta} &= \frac{3\alpha+3\beta G+3\theta H^{TR,\theta}+\gamma c}{4\gamma},\\ Q^{TR,\theta} &= \frac{\tau}{\xi}(D_1^{TR,\theta}G+D_2^{TR,\theta}),\\ H^{TR,\theta} &= \frac{\lambda(D_1^{TR,\theta}G+D_2^{TR,\theta})+\theta(\alpha+\beta G-\gamma c)/(4\gamma)}{\Delta_R},\\ I^{TR,\theta} &= \frac{\varepsilon}{\mu}(F_1^{TR,\theta}G+F_2^{TR,\theta}). \end{aligned} \tag{9.3}$$

The manufacturer's and platform's value functions are given, respectively, by

$$\begin{aligned} J_m^{TR,\theta} &= \frac{1}{2}D_1^{TR,\theta}G^2+D_2^{TR,\theta}G+D_3^{TR,\theta},\\ J_e^{TR,\theta} &= \frac{1}{2}F_1^{TR,\theta}G^2+F_2^{TR,\theta}G+F_3^{TR,\theta}. \end{aligned} \tag{9.4}$$

The coefficients $D_i^{TR,\theta}$ and $F_i^{TR,\theta}$, i=1,2,3, and the equilibrium green goodwill are calculated in the proof.

Proof. See Appendix H.1. □

Proposition 8. *In Case TA,θ, the unique feedback Stackelberg equilibrium strategies are given by*

$$\begin{aligned} P^{TA,\theta} &= \frac{1}{2}\left(\frac{\alpha+\beta G+\theta H^{TA,\theta}}{\gamma}+\frac{c}{1-\varphi}\right),\\ Q^{TA,\theta} &= \frac{\tau}{\xi}(K_1^{TA,\theta}G+K_2^{TA,\theta}),\\ H^{TA,\theta} &= \frac{\lambda(K_1^{TA,\theta}G+K_2^{TA,\theta})+\theta[(1-\varphi)(\alpha+\beta G)-\gamma c]/(2\gamma)}{\Delta_A},\\ I^{TA,\theta} &= \frac{\varepsilon}{\mu}(L_1^{TA,\theta}G+L_2^{TA,\theta}). \end{aligned} \tag{9.5}$$

The manufacturer's and platform's value functions are given, respectively, by

$$\begin{aligned} J_m^{TA,\theta} &= \frac{1}{2}K_1^{TA,\theta}G^2+K_2^{TA,\theta}G+K_3^{TA,\theta},\\ J_e^{TA,\theta} &= \frac{1}{2}L_1^{TA,\theta}G^2+L_2^{TA,\theta}G+L_3^{TA,\theta}. \end{aligned} \tag{9.6}$$

The coefficients $K_i^{TR,\theta}$ and $L_i^{TR,\theta}$, i=1,2,3, and the equilibrium green goodwill are calculated in the proof.

Proof. See Appendix H.2. □

Based on the above equilibrium results, the following proposition compares the extended cases with the traffic support cases in terms of the manufacturer's relative allocation of effort between quality improvement and carbon emission reduction.

Proposition 9. *At the same level of the manufacturer's green goodwill G, with all other parameters held fixed, suppose that the manufacturer's marginal value of green goodwill is* $v_j^{\theta}(G) \equiv \frac{dJ_m^{j,\theta}(G)}{dG} > 0$. *To express the two sales modes uniformly, define*

$$M_j^{\theta}(G) = \begin{cases} [W^{TR,\theta}(G) - c]/2, & j = TR, \\ (1-\varphi)P^{TA,\theta}(G) - c, & j = TA. \end{cases} \tag{9.7}$$

Then, for any $\theta > 0$ *satisfying the above conditions, we have*

$$R_j^{\theta}(G) - R_j^0 = \frac{\xi\theta M_j^{\theta}(G)}{\eta\tau v_j^{\theta}(G)} > 0. \tag{9.8}$$

Here, $R_j^{\theta}(G) \equiv \frac{H^{j,\theta}(G)}{Q^{j,\theta}(G)}$ *is the ratio of carbon emission reduction effort to quality improvement effort in the extended case;* $R_j^0 = \frac{H^j(G)}{Q^j(G)} = \frac{\lambda\xi}{(\eta\tau)}$ *is the corresponding ratio of carbon emission reduction effort to quality improvement effort in Case TR or TA. Consequently, the share of carbon emission reduction expenditure in the manufacturer's total cost of the two efforts satisfies*

$$S_H^{j,\theta}(G) > S_H^{j}(G) = S_H^{j,0}. \tag{9.9}$$

Here, $S_H^{j,\theta}(G) \equiv \frac{\eta[H^{j,\theta}(G)]^2}{\xi[Q^{j,\theta}(G)]^2+\eta[H^{j,\theta}(G)]^2}$ *is the share of carbon emission reduction expenditure in the manufacturer's total cost of the two efforts in the extended case;* $S_H^{j,0}(G) = \frac{\lambda^2\xi}{\eta\tau^2+\lambda^2\xi}$ *is the corresponding share of carbon emission reduction expenditure in Case TR or TA.*

Proof. See Appendix H.3. □

Proposition 9 shows that, under both reselling and agency selling, at a common green goodwill state G, with the other parameters fixed and the conditions in the proposition satisfied, the ratio of carbon emission reduction effort to quality improvement effort in the extended case with $\theta > 0$ is higher than in the corresponding TR or TA case. The share of carbon emission reduction expenditure in the manufacturer's total spending on the two efforts also increases. This occurs because the additional demand term θH gives carbon emission reduction effort an extra current-period marginal operating return beyond the dynamic return from goodwill accumulation, thereby changing the fixed investment ratio determined by τ, λ, ξ, and η in TR and TA.

10. Conclusions and implications

Motivated by the platform practice of providing traffic support to products in low-carbon zones, this study develops a manufacturer-led feedback Stackelberg differential game model, with green goodwill as the dynamic state variable, to examine the interactions between the platform's traffic support and the manufacturer's quality improvement and carbon emission reduction decisions. By combining the traffic support model, the low-carbon model, and the traditional model with the reselling and agency modes,

this study compares equilibrium decisions, green goodwill evolution, and supply chain members' payoff values across six operational cases. The theoretical and numerical analyses yield the following main findings.

First, under the parameter settings considered, traffic support in the low-carbon zone strengthens the manufacturer's incentives for quality improvement and carbon emission reduction. Compared with the low-carbon model without traffic support, the traffic support model yields higher quality improvement and carbon emission reduction efforts, faster green goodwill accumulation, and higher payoff values for both supply chain members. Although the low-carbon model generates higher green goodwill than the traditional model, the manufacturer's quality improvement effort and payoff value are similar across these two models in the plotted results. These comparisons distinguish the effects of carbon emission reduction from those of the platform's traffic support, indicating that low-carbon zone participation with traffic support provides additional effort incentives for the manufacturer.

Second, sales modes have different effects on supply chain members' effort incentives and payoff values. Under the parameter values examined, agency selling yields higher quality improvement effort by the manufacturer and lower retail prices across the three models. The retail price ranking is conditional on the commission rate and the green goodwill levels attained under the respective modes, as characterized in Corollary 3. In the traffic support and low-carbon models, the manufacturer's carbon emission reduction effort is also higher under the agency mode. Although the platform provides more traffic support under the reselling mode in the traffic support model, the manufacturer's higher effort levels under the agency mode still lead to higher green goodwill. The manufacturer obtains higher payoff values under the agency mode in all three models. For the platform, the payoff–value curves for Cases TR and TA, as well as those for Cases LR and LA, intersect over time: Reselling offers higher payoff values initially, whereas agency selling yields higher payoff values subsequently. In the traditional model, the platform's payoff value in Case BR exceeds that in Case BA over the period examined. These results indicate that the manufacturer's and platform's payoff rankings across sales modes are not fully aligned. Sales mode evaluation should therefore account for both members' effort incentives and green goodwill accumulation, rather than relying solely on initial payoff rankings.

Third, green goodwill formation and the manufacturer's effort incentives are jointly influenced by the relevant impact coefficients and the platform's traffic support cost coefficient. In the traffic support model, within the parameter ranges examined, increases in the impact coefficients of quality improvement, carbon emission reduction, and traffic support on green goodwill increase green goodwill and both members' payoff values. In particular, a higher impact coefficient of traffic support on green goodwill also increases the manufacturer's quality improvement and carbon emission reduction efforts, whereas a higher traffic support cost coefficient reduces both efforts. This finding indicates that the platform's traffic support cost constraints affect not only its own operational decisions but also, indirectly, the manufacturer's incentives for quality improvement and carbon emission reduction. Moreover, the extended model shows that when carbon emission reduction effort directly affects current demand, the manufacturer allocates relatively more effort and expenditure to carbon emission reduction than in the corresponding baseline traffic support cases.

These findings provide several managerial implications. For the manufacturer, preference may be given to the agency mode to enhance green goodwill and future discounted payoffs. Under the parameter values examined, the manufacturer may prefer the agency mode because it yields higher green goodwill and future discounted payoffs. However, in the traditional and low-carbon models, its long-run sales

mode preference depends on the commission rate threshold identified in Corollary 2. In the traffic support and low-carbon models, the platform obtains higher payoff values under the reselling mode initially, whereas the agency mode becomes more advantageous subsequently. In the traditional model, reselling offers the platform a payoff advantage over the period examined.

This study has several limitations. First, quadratic effort cost functions are adopted. Future research could consider alternative nonquadratic convex cost functions to examine how different cost structures affect the equilibrium results. Second, this study considers only a single manufacturer and a single platform. Future research could extend the model to competitive settings with multiple manufacturers or platforms to investigate how competition affects quality improvement, carbon emission reduction, and sales mode selection. In addition, consumer heterogeneity, the platform's recommendation mechanisms, and government low-carbon subsidy policies could be incorporated to broaden the applicability of the model. Future research could examine traffic allocation contingent on verified environmental attributes and its direct effects on current demand.

Author contributions

Xueli Xin: Conceptualization, methodology, investigation, formal analysis, writing – original draft, and writing – review and editing; Tianwei Chen: Conceptualization, investigation, formal analysis, and writing – review and editing; Rong Xin: Conceptualization, methodology, supervision, resources, and writing – review and editing. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of Generative-AI tools declaration

The authors declare that no artificial intelligence (AI) tools were used in the creation of this manuscript.

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