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The Intelligent Upgrading of Logistics between an Internet Enterprise and a Logistics Enterprise Based on Differential Game Theory

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Abstract: At the background of "Internet + Logistics", intelligent logistics has high operational efficiency and provides a superior customer experience, meeting the requirements of sustainable development. It also plays a crucial role in promoting the modernization of the industrial chain in China. This paper develops a mathematic model based on differential game theory, which sets the intelligent level of logistics and the goodwill of intelligent logistics as state variables. The research reveals the collaborative strategies between a logistics enterprise and an Internet enterprise for the intelligent upgrading of logistics, and separately calculates the optimal effort levels and optimal revenues of participating enterprises under the non-cooperative mechanism, the cost-sharing mechanism, and the cooperative mechanism. This paper also observes the crucial parameters that affect the optimal revenue for the intelligent upgrading of logistics. The research findings are as follows: (1) Cost-sharing mechanism and cooperative mechanism can motivate the Internet enterprise and the logistics enterprise to improve their effort levels and increase the total revenue, which achieves the Pareto improvement. Under the cooperative mechanism, the intelligent level of logistics and the goodwill of intelligent logistics are the highest. (2) Participating enterprises can promote the intelligent upgrading of logistics by accumulating innovative resources for intelligent logistics, attaining cost-conversion efficiency, and cultivating customer preferences for intelligent logistics services. (3) When the revenue-sharing ratio of the logistics enterprise is relatively low, although the cost-sharing mechanism can continuously motivate a logistics enterprise to make an effort in the intelligent upgrading of logistics, it is not conducive to enhance the goodwill of intelligent logistics. This paper highlights the pivotal role of enterprise collaboration in the intelligent upgrading of logistics, and proposes practical recommendations.

Keywords: intelligent upgrading of logistics; Internet enterprises; collaboration; intelligent logistics; differential game theory

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1. Introduction

The logistics industry is a key pillar of the national economy, and plays a crucial role in promoting industrial structure upgrading [1], enhancing the radiation effect of central cities [2], and reinforcing supply chain resilience [3]. The ongoing advancements in the utilization of the Internet of Things, Big Data, and artificial intelligence within traditional industries are bringing a transformation in the logistics sector from the conventional collegial mode towards a cross-industry integrated intelligent development framework [4]. Intelligent logistics encompasses the thorough amalgamation of information technology and the logistics industry, achieving refined, dynamic, and visually managed logistics processes through intelligent software and hardware, the IoT, and other intelligent technologies [5,6]. The intelligent logistics model is equipped with intelligent decision-making capacity and self-learning capacity, which can bolster the risk-taking capacity of supply chain and effectively coping with uncertainties.

The relevant data show that the Chinese market scale of logistics has reached 699.5 billion yuan in 2022, with a year-on-year growth of 8% [7]. The continuous expansion of the domestic consumer market and the scale of cross-border trade is an important driving force for the development of intelligent logistics. However, China's intelligent logistics is still in the preliminary stage of development, and the intelligence level of logistics remains weak among the majority of logistics enterprises [8]. On the one hand, due to the undeveloped intelligent infrastructure in the logistics industry and regional disparities, it is difficult to leverage the function of information sharing, which limits the application of cutting-edge technologies such as artificial intelligence and blockchain [9], resulting in limited economic returns. On the other hand, as the logistics industry requires cross-regional operations and cross-industry integration, it requires upstream and downstream enterprises in the supply chain to implement a coherent information technology standard system [4], including data coding, data interface, and electronic data interchange (EDI). However, most logistics enterprises, suppliers, and customers are unwilling to adopt a coherent information standard, and the imbalanced development of the upstream and downstream of the supply chain is prominent [10]. It results that the competitive advantages based on enterprise collaboration cannot be applied in intelligent logistics.

With the aim of achieving the intelligent upgrading of logistics, logistics enterprises should address several prominent challenges, including technological adaptation, the standardization of information, and the integration of upstream and downstream resources. However, traditional logistics enterprises, often constrained by insufficient technological capability [11], cannot satisfy the requirements for the intelligentization of logistics. Consequently, they have a high willingness to collaborate with Internet enterprises, which can support adequate resources for intelligent development. Meanwhile, Internet enterprises are also urgent to overcome these obstacles like market saturation [12], homogeneous competition, and others. Therefore, it is imperative for Internet enterprises to actively find new opportunities for revenue expansion and cultivate the distinctive competence [13].

In the context of the intelligent upgrading of logistics, Internet enterprises can leverage Big Data technology and high-volume data resources to develop and provide more precise demand forecasting and route planning software for logistics enterprises, which aims to reduce the delivery time and minimize empty loading ratios. Additionally, Internet enterprises will collaborate with logistics enterprises to establish an intelligent warehousing system, achieving the intelligent management and automated handling of warehouse goods. The system plays an important role in enhancing storage density, decreasing scheduling frequency, improving inventory management efficiency, and reducing capital occupancy costs. Furthermore, it is essential for collaborative enterprises to establish an intelligent logistics information platform with the support of cloud computing and blockchain technology, which can track the goods in transportation and provide logistics information to customers in real-time, thereby improving the supply chain transparency and customer experience. Lastly, both participating enterprises can jointly formulate, promote, and enforce intelligent logistics standards to enhance the compatibility of the supply chain.

It is worth noting that most logistics enterprises were originally engaged in single business transport or warehousing services, and their management systems and information infrastructure need to be improved. How can logistics enterprises effectively attract Internet enterprises with ample capital and innovative resources to establish enduring partnerships and collectively advance the integration of intelligent technologies within the logistics sector? Furthermore, how can Internet enterprises motivate traditional logistics enterprises to spare no effects to promote the intelligentization of logistics? Participating enterprises must clearly define the mechanism for assigning contributions and coordinating revenues during the collaborative process. Furthermore, given the current low market penetration of intelligent logistics, it is imperative for logistics enterprises to dedicate advertising and promotions to intelligent logistics that cultivate the goodwill of intelligent logistics, which is essential to accumulate customers and enhance the long-term revenue from the intelligent upgrading of logistics.

In summary, the paper investigates the dynamic game solutions for the intelligent upgrading of logistics from the collaborative perspective between an Internet enterprise and a logistics enterprise. Firstly, the paper reviews extant literature about intelligent logistics and the enterprise collaborative mechanism, then identifies research gaps and outlines the innovative direction. Subsequently, the paper demonstrates the research problem and proposes research assumptions. Then, a differential game model is developed to incorporate state variables representing the intelligent level of logistics and the goodwill of intelligent logistics. This model is to derive the optimal strategies for participating enterprises under three different collaborative mechanisms. Finally, numerical simulations are employed to validate the optimal strategies under three mechanisms. Additionally, the paper also summarizes the crucial factors that affect the revenue from the intelligent upgrading of logistics.

2. Literature Reviews

2.1. Research on the Intelligent Upgrading of Logistics

The concept of intelligent logistics, also known as smart logistics, originated from the "Intelligent Logistics System" proposed by the International Business Machines Corporation (IBM) in 2009 [14]. As the frontier research topics, relevant studies on intelligent logistics mainly focus on the construction of theoretical frameworks, intelligent logistics platforms and management systems, and empirical research. In terms of theoretical framework construction, Nowicka (2014) proposed a logistics framework for a smart city based on a cloud computing model [15]; Calatayud and Mangan (2019) argue that future supply chains should have autonomous decision-making and predictive capability [16], and that the Internet of Things and blockchain can enhance information sharing efficiency and protect data privacy [17], which plays a crucial role in promoting the transformation of the traditional supply chain into the "self-thinking supply chain"; and Feng and Ye (2021) reviewed relevant literature on the application of intelligent logistics technology, operational frameworks, and optimization issues [18], recommending that scholars should pay more attention to intelligent logistics visualization and collaborative mechanisms with other intelligent modules including smart transportation and smart cities. Intelligent logistics platforms should be equipped with real-time response capabilities [19], and artificial intelligence technology can significantly improve the operational efficiency of logistics systems and promptly rectify the uncertainties in the operational processes [20]. Roman (2023) established an intelligent logistics system that achieves self-configuration, management, and protection through database and artificial intelligence technology [21], and is capable of adapting to unstable operating environments.

In terms of empirical research on the intelligent upgrading of logistics, several studies have shown that internal factors like talent cultivation and Internet infrastructure, along with external factors such as government regulation and industry standards, can drive the intelligent upgrading of logistics [3,22], which is conducive to improving the financial performance of the enterprise. Shee et. al. (2021) argued a complementary relation in the development of intelligent logistics and the smart city from the Technology, Organisation, and Environment (TOE) perspective [23]. Liu et al. (2022) confirmed that lower data-sharing costs and reasonable platform commission fees consolidated the cooperation between intelligent logistics platforms and suppliers [24]. Gu and Zhang (2023) developed an evaluation system to analyze the intelligent level of the logistics industry by the entropy weight method, gravity model, and social network analysis, and found that the intensity of the spatial linkage of the intelligentization of the logistics industry in the eastern area of China is higher than that in the western area of China [25]. They also validated that regional innovation ability, economic performance, and educational quality can significantly enhance the spatial linkage strength of intelligentization in the logistics industry. Fan (2024) further constructed an evaluation system to measure the intelligent capacity of the logistics enterprise [26], and found that the capability promoting the intelligentization of logistics enterprises is mainly reflected in four dimensions, including technological innovation, data sharing, management improvement, and logistics decision-making transformation.

2.2. Research on the Collaborative Mechanisms of Logistics Enterprises

Collaboration mechanisms play a vital role in enabling enterprises to leverage resource complementarity, diversify risks, and expand marketing channels [27]. It allows enterprises to overcome innovation bottlenecks and enhance economic performance in the short term. Notably, supply chain collaboration serves as a pivotal mechanism for both upstream and downstream enterprises to bolster their competitiveness [28]. While extant research on supply chain collaboration mainly centers around downstream suppliers and upstream merchants, investigating how policy regulation [29,30] and digital empowerment [31] impact the innovation behavior and profitability of collaborative enterprises through mathematical modeling and game theory, there exists a research gap on the collaborative behavior of logistics enterprises. Yang et al. (2023) reveal that the risk costs stemming from supply chain disruptions impede collaboration among cross-border e-commerce platforms, logistics service providers, and merchants [32]. Furthermore, logistics service providers exhibit reluctance to pursue service innovation strategies due to platform penalties. Additionally, technological revenue enablement, information sharing, and subsidy policies also exert influence on the willingness of logistics enterprises to make efforts in collaborative innovation [33]. Zhang et al. (2024) found that the government adopts reasonable subsidies for logistics associations and maintains the autonomy of logistics associations [34], which can realize cooperative supervision and healthy competition among the government, logistics associations, and logistics enterprises.

2.3. Research Gap and Contribution

In conclusion, this paper argues that extant research still needs the following for improvement: (1) The existing research has summarized the significant variables that affect the intelligent upgrading of logistics; few studies portray the dynamic process of the intelligent upgrading of logistics through game theory. (2) The extant literature mainly focuses on the collaborative strategy between logistics enterprises and other supply chain members. However, the collaborative strategies and revenue coordination mechanisms between logistics enterprises and Internet enterprises, as long-term stakeholders of the supply chain, are still to be explored. (3) Given that intelligent logistics is an emerging business mode, logistics enterprises will strengthen customer preference and value perception through advertising and marketing to increase the market volume of intelligent logistics services [35]. Existing research papers consider the impact of advertising and promotion effort in many research fields through game theory and mathematical simulation, including carbon emission reduction, supply chain coordination, and product innovation. Li et al. (2018) introduce the concept of low-carbon promotional effort to examine a cooperative strategy for carbon emission reduction in the closed-loop supply chain [36]. Taboubi (2019) finds that an advertising allowance offered by the manufacturer to the retailer help mitigate the double-marginalization problem in supply chain pricing [37]. Yi and Tang (2024) demonstrate that a subsidy contract for R&D and production innovation promotion offered by the manufacturer can effectively improve the goodwill of product innovation for the supplier and the retailer in the supply chain [38].

The major contribution can be summarized as follows: Firstly, this paper demonstrates and displays the dynamic process of the intelligentization of logistics based on differential game theory, discusses the optimal coordinative strategy of participating enterprises under different collaborative mechanisms, and further analyzes the potential factors that impact the revenue of the intelligent upgrading of logistics, like the proportion of revenue distribution and intelligent technological adaptability. Secondly, this study innovatively introduces the intelligent level of logistics and the goodwill of the intelligent logistics as state variables, which will more objectively simulate the dynamic trend of the intelligent upgrading of the logistics. Finally, the findings in this paper enrich the theoretical research on the intelligent upgrading of logistics, providing practical recommendations for logistics enterprises to develop intelligent logistics through cross-industry collaboration against the background of "Internet+".

3. Problem Description and Model Assumption

The intelligent upgrading of logistics has the potential to reduce operational costs, stimulate customer demand, and cultivate a brand image with high technology for the participating enterprise, which is beneficial to improve revenue. To investigate the strategy of the participating enterprises for the intelligent upgrading of logistics under different collaborative mechanisms, this paper considered an alliance for the intelligent upgrading of logistics consisting of an Internet enterprise (I) and a logistics enterprise (L). The participating enterprises put together a cooperation agreement on these aspects, including the construction of intelligent infrastructure, data sharing, and visualization, the operational optimization of logistics and the standardization of intelligent logistics to improve the intelligent level of logistics. Meanwhile, the logistics enterprise also enhances the goodwill of intelligent logistics through advertising and marketing, which ultimately generate revenue. The above theoretical framework can be depicted in Figure 1.

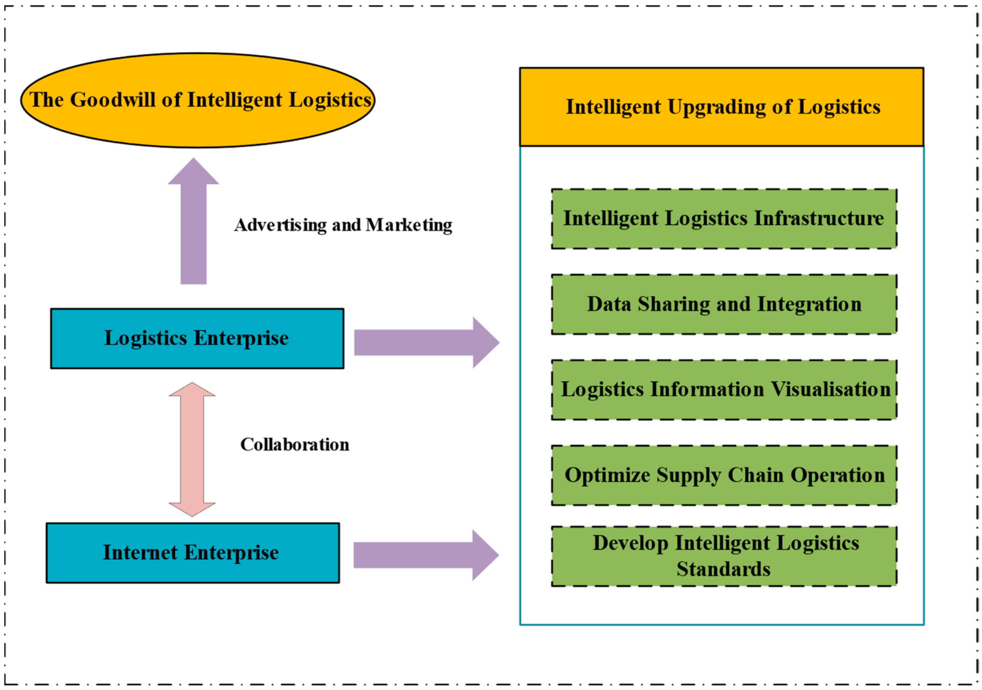


Figure 1. The theoretical framework for the intelligentization of logistics between an Internet enterprise and a logistics enterprise.

In reference to the problem description, the paper proposes the following assumptions:

Assumption 1. The cost of the intelligent upgrading of logistics is a convex function [39] of the level of effort for the Internet enterprise and the logistics enterprise. Therefore, the cost functions of the Internet enterprise (I) and the logistics enterprise (L) at time t can be expressed as follows:

$$C_I(t) = (\frac{\mu_I}{2} + \frac{1}{k_I})E_I{}^2(t);\ C_L(t) = (\frac{\mu_L}{2} + \frac{1}{k_L})E_L{}^2(t) \tag{1}$$

where μ_I and μ_L denote the cost coefficients of the intelligent upgrading for the Internet enterprise and the logistics enterprise. $E_I(t)$ and $E_L(t)$ denote the level of effort exerted by the Internet enterprise and the logistics enterprise at time t, respectively. k_I and k_L

denote the technological adaptability for the Internet enterprise and the logistics enterprise, respectively. This reflects the similarity between the existing and the newly introduced technology, as well as the level of technological diversification [40]. Higher technological adaptability implies that enterprises are more capable of making technological advancement in the mix of inbound and outbound open innovation [41,42], which is beneficial for reducing expenditures on technology acquisition and absorption.

Assumption 2. The intelligentization of logistics involves an ongoing process that necessitates continuous efforts and accumulation from both participating enterprises. According to the kinematics equation presented in Ref. [43], which encapsulates the knowledge accumulation process, the intelligent level of logistics $X(t)$ is treated as a state variable. It is influenced by the effort of participating enterprises.

$$\dot{X}(t) = \lambda_I E_I(t) + \lambda_L E_L(t) - \delta X(t) \tag{2}$$

where λ_I and λ_L denote the marginal coefficient of the efforts made by the both participating enterprises promoting the intelligent upgrading of logistics. δ denotes the natural decay factor of the intelligent level of logistics, which reflects the natural decay effect of technology iteration and equipment replacement. The initial intelligent level of logistics is set to $X(0) = X_0 > 0$.

Assumption 3. The logistics enterprise will cultivate the goodwill of smart logistics through marketing campaigns, including content marketing, offline exhibitions, and the establishment of customer feedback mechanisms. This paper uses the N-A model to characterize the impact of marketing efforts on the goodwill of intelligent logistics [44]. The kinematics equation for the goodwill of intelligent logistics can be expressed as follows:

$$\dot{R}(t) = \varphi M(t) - \psi R(t) \tag{3}$$

where $R(t)$ denotes the goodwill of intelligent logistics at time t. $M(t)$ denotes the marketing effort of the logistics enterprise at time t. φ represents the efficiency of the marketing cost of intelligent logistics to improve the goodwill of intelligent logistics. ψ represents the natural decay factor of the goodwill of logistics. The initial goodwill of intelligent logistics is set to $R(0) = R_0 > 0$.

Accordingly, the marketing cost function of the logistics enterprise $C_R(t)$ is shown in Equation (4); μ_R denotes the coefficient of the marketing cost for the logistics enterprise.

$$C_R(t) = \frac{\mu_R}{2} M^2(t) \tag{4}$$

Assumption 4. The intelligent level of logistics and the goodwill of intelligent logistics directly affect the total revenue of the participating enterprises from the intelligent upgrading of logistics. Therefore, the total revenue generated by the intelligent upgrading of logistics at time t can be denoted as follows:

$$\pi(t) = \gamma X(t) + \eta R(t) \tag{5}$$

γ and η are the coefficients that reflect the contribution of the intelligent level of logistics and the goodwill of intelligent logistics to the total revenue.

Assumption 5. The Internet enterprise and the logistics enterprise distribute the total revenue in proportion to θ and $(1-\theta)$ in the intelligent upgrading of logistics.

Assumption 6. Under the cost-sharing mechanism, to motivate the logistics enterprise to actively engage in the intelligentization of logistics, the Internet enterprise with high levels of intelligent technology and sufficient funds will offer a cost allowance to the logistics enterprise. Here, $w \in [0,1]$ denotes the cost-sharing ratio.

Assumption 7. The discount rate $\rho(>0)$ is identical for the Internet enterprise and logistics enterprise, and the discount rate remains constant at any time. Both participating enterprises maximize their revenue in the infinite period. $\varepsilon_I(>0)$ and $\varepsilon_L(>0)$ represent the normal revenues obtained by both participating enterprises.

The above equations contain the control variables $E_I(t)$, $E_L(t)$, and $M(t)$, and the state variables $X(t)$ and $R(t)$. If the parameters change with time, the subsequent differential game model cannot be solved, so the paper assumes that all parameters in the model are positive constants. If the Internet enterprise and the logistics enterprise are in the same game scenario at any time, the participating enterprises make static decisions [45] and the corresponding static feedback equilibrium can be obtained.

4. Model Construction and Solution

4.1. The Game Theory Model under the Non-Cooperative Mechanism

Under the non-cooperative mechanism, the Internet enterprise and the logistics enterprise independently decide their own level of effort, and the logistics enterprise independently determines the marketing cost of intelligent logistics in order to maximize its own revenue. Correspondingly, the optimal strategy combination of participating enterprises converges to a static feedback Nash equilibrium. The objective revenue functions of the Internet enterprise and the logistics enterprise are shown in Equations (6) and (7).

$$\max J_I^N = \int_0^\infty e^{-\rho t}[\theta(\gamma X(t) + \eta R(t)) + \varepsilon_I - C_I(t)]dt \tag{6}$$

$$\max J_L^N = \int_0^\infty e^{-\rho t}[(1-\theta)(\gamma X(t) + \eta R(t)) + \varepsilon_L - C_L(t) - C_R(t)]dt \tag{7}$$

Let V_I and V_L denote the optimal revenue functions of the Internet enterprise and the logistics enterprise, respectively. When $X, R \geq 0$, both V_I and V_L are continuous, bounded, and differentiable. They satisfy the following Hamilton–Jacobi–Bellman (HJB) equations:

$$\rho V_I = \max_{E_I}\{\theta(\gamma X(t) + \eta R(t)) + \varepsilon_I - (\frac{\mu_I}{2} + \frac{1}{k_I})E_I{}^2(t) + V'_{I1}(\lambda_I E_I(t) + \lambda_L E_L(t) - \delta X(t)) + V'_{I2}(\varphi M(t) - \psi R(t))\} \tag{8}$$

$$\begin{aligned} \rho V_L = \max_{E_L, M}\{&\theta(\gamma X(t) + \eta R(t)) + \varepsilon_L - (\tfrac{\mu_L}{2} + \tfrac{1}{k_L})E_L{}^2(t) - \tfrac{\mu_R}{2}M^2(t) + \\ &V'_{L1}(\lambda_I E_I(t) + \lambda_L E_L(t) - \delta X(t)) + V'_{L2}(\varphi M(t) - \psi R(t))\} \end{aligned} \tag{9}$$

By calculating the partial derivative of the right side of Equation (8) with respect to E_I, and then calculating the partial derivatives of Equation (9) with respect to E_L and M, further setting them to zero, the following solutions can be obtained:

$$(E_I^N, E_L^N, M^N) = (\frac{\lambda_I V'_{I1}}{(\mu_I + \frac{2}{k_I})}, \frac{\lambda_L V'_{L1}}{(\mu_L + \frac{2}{k_L})}, \frac{\varphi V'_{L2}}{\mu_R}) \tag{10}$$

Substitute Equation (10) into Equations (8) and (9) and simplify them as follows:

$$\rho V_I = \max\{(\theta\gamma - V'_{I1}\delta)X(t) + (\theta\eta - V'_{I2}\psi)R(t) + \frac{\lambda_I{}^2(V'_{I1})^2}{2(\mu_I + \frac{2}{k_I})} + \frac{\lambda_L{}^2 V'_{I1} V'_{L1}}{(\mu_L + \frac{2}{k_L})} + \frac{\varphi^2 V'_{I2} V'_{L2}}{\mu_R} + \varepsilon_I\} \tag{11}$$

$$\rho V_L = \max\{((1-\theta)\gamma - V'_{L1}\delta)X(t) + ((1-\theta)\eta - V'_{L2}\psi)R(t) + \frac{\lambda_L{}^2(V'_{L1})^2}{2(\mu_L + \frac{2}{k_L})} + \frac{\lambda_I{}^2 V'_{I1} V'_{L1}}{(\mu_I + \frac{2}{k_I})} + \frac{\varphi^2(V'_{L2})^2}{2\mu_R} + \varepsilon_L\} \tag{12}$$

From Equations (11) and (12), it is known that the solution to the HJB equation is a linear function of two variables, X and R. Let

$$V_I^N = f_I^N X(t) + g_I^N R(t) + m_I^N; V_L^N = f_L^N X(t) + g_L^N R(t) + m_L^N \tag{13}$$

where the parameters in Equation (13) are constants except X and R. Taking partial derivatives of Equations (11) and (12) with respect to X and R, further setting them to zero, the parameter values of f_I^N, f_L^N, g_I^N, g_L^N, m_I^N, and m_L^N can be calculated as follows:

$$f_I^N = V'_{I1} = \frac{\theta\gamma}{\rho+\delta},\ g_I^N = V'_{I2} = \frac{\theta\eta}{\rho+\psi};\ f_L^N = V'_{L1} = \frac{(1-\theta)\gamma}{\rho+\delta},\ g_L^N = V'_{L2} = \frac{(1-\theta)\eta}{\rho+\psi} \tag{14}$$

$$m_I^N = \frac{1}{\rho}\{\frac{\theta^2\lambda_I^2\gamma^2}{2(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{\theta(1-\theta)\lambda_L^2\gamma^2}{(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{\theta(1-\theta)\varphi^2\eta^2}{\mu_R(\rho+\psi)^2} + \varepsilon_I\} \tag{15}$$

$$m_L^N = \frac{1}{\rho}\{\frac{(1-\theta)^2\lambda_L^2\gamma^2}{2(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{\theta(1-\theta)\lambda_I^2\gamma^2}{(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{(1-\theta)^2\varphi^2\eta^2}{2\mu_R(\rho+\psi)^2} + \varepsilon_L\} \tag{16}$$

Substitute Equation (14) into Equation (10), the optimal effort level of both participating enterprises, and the optimal marketing effort level of the logistics enterprise can be obtained as follows:

$$(E_I^{N^*}, E_L^{N^*}, M^{N^*}) = (\frac{\lambda_I k_I\theta\gamma}{(\rho+\delta)(k_I\mu_I+2)}, \frac{\lambda_L k_L(1-\theta)\gamma}{(\rho+\delta)(k_L\mu_L+2)}, \frac{(1-\theta)\varphi\eta}{(\rho+\psi)\mu_R}) \tag{17}$$

It can be known that the optimal revenue functions of the Internet enterprise and the logistics enterprise under the non-cooperative mechanism as well as their optimal total revenue function are, respectively, as follows:

$$V_I^N(t) = \frac{\theta\gamma}{\rho+\delta}X(t) + \frac{\theta\eta}{\rho+\psi}R(t) + \frac{1}{\rho}\{\frac{\theta^2\lambda_I^2\gamma^2}{2(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{\theta(1-\theta)\lambda_L^2\gamma^2}{(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{\theta(1-\theta)\varphi^2\eta^2}{\mu_R(\rho+\psi)^2} + \varepsilon_I\} \tag{18}$$

$$V_L^N(t) = \frac{(1-\theta)\gamma}{\rho+\delta}X(t) + \frac{(1-\theta)\eta}{\rho+\psi}R(t) + \frac{1}{\rho}\{\frac{(1-\theta)^2\lambda_L^2\gamma^2}{2(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{(1-\theta)\theta\lambda_I^2\gamma^2}{(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{(1-\theta)^2\varphi^2\eta^2}{2\mu_R(\rho+\psi)^2} + \varepsilon_L\} \tag{19}$$

$$V_T^N(t) = \frac{\gamma}{\rho+\delta}X(t) + \frac{\eta}{\rho+\psi}R(t) + \frac{1}{\rho}\{\frac{(1-\theta^2)\lambda_L^2\gamma^2}{2(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{(2-\theta)\theta\lambda_I^2\gamma^2}{2(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{(1-\theta^2)\varphi^2\eta^2}{2\mu_R(\rho+\psi)^2} + \varepsilon_I + \varepsilon_L\} \tag{20}$$

4.2. The Game Theory Model under the Cooperative Mechanism

Under the cooperative mechanism, the Internet enterprise and the logistics enterprise collaborate to achieve a synergistic development strategy and utilize organizational resources effectively, with the aim of establishing a unified body of shared revenue. In order to maximize overall revenue, both parties engage in negotiations to determine the optimal strategies and revenue function. This serves to enhance the intelligent level of logistics and foster positive customer perceptions towards intelligent logistics. The overall target revenue function can be expressed as follows:

$$\max J^C = \int_0^\infty e^{-\rho t}[(\varepsilon_I+\varepsilon_L+\gamma X(t)+\eta R(t)) - C_I(t) - C_L(t) - C_R(t)]dt \tag{21}$$

The optimal revenue function $V(X,R)$ should conform to the HJB equation as follows:

$$\begin{aligned}\rho V(X,R) = \max_{E_I,E_L,M}\{&(\varepsilon_I+\varepsilon_L+\gamma X(t)+\eta R(t)) - (\tfrac{\mu_I}{2}+\tfrac{1}{k_I})E_I^2(t) - (\tfrac{\mu_L}{2}+\tfrac{1}{k_L})E_L^2(t) - \tfrac{\mu_R}{2}M^2(t)+\\ &V'_X(\lambda_I E_I(t)+\lambda_L E_L(t)-\delta X(t)) + V'_R(\varphi M(t)-\psi R(t))\}\end{aligned} \tag{22}$$

The procedure for solving the game model under the cooperative mechanism shares similarities with that of the non-cooperative mechanism, but due to space limitations, the detailed process is omitted. The optimal solutions for the control variables E_I^C, E_L^C, and M^C are as follows:

$$(E_I^{C^*}, E_L^{C^*}, M^{C^*}) = (\frac{\lambda_I k_I \gamma}{(\mu_I k_I + 2)(\rho + \delta)}, \frac{\lambda_L k_L \gamma}{(\mu_L k_L + 2)(\rho + \delta)}, \frac{\varphi \eta}{\mu_R(\rho + \psi)}) \tag{23}$$

The optimal total revenue function can be expressed as follows:

$$V_T^C(t) = \frac{\gamma}{\rho + \delta} X(t) + \frac{\eta}{\rho + \psi} R(t) + \frac{1}{\rho} \{ \frac{\lambda_I^2 \gamma^2}{2(\mu_I + \frac{2}{k_I})(\rho + \delta)^2} + \frac{\lambda_L^2 \gamma^2}{2(\mu_L + \frac{2}{k_L})(\rho + \delta)^2} + \frac{\varphi^2 \eta^2}{2\mu_R(\rho + \psi)^2} + \varepsilon_I + \varepsilon_L \} \tag{24}$$

4.3. The Game Theory Model under the Cost-Sharing Mechanism

Under the cost-sharing mechanism, the Internet enterprise plays a leading role in the intelligent upgrading of logistics. It shares cost with the logistics enterprise, taking into account the proportion of revenue distribution. Upon receiving the Internet enterprise's cost-sharing decision, the logistics enterprise takes a responsive measure to maximize its own revenue. Meanwhile, the Internet enterprise can anticipate the logistics enterprise's responsive measure prior to making its final decision. Consequently, the inverse induction method is employed to determine the Stackelberg equilibrium in the cost-sharing scenario. The objective revenue functions for both participating enterprises are presented as follows:

$$\max J_I^S = \int_0^\infty e^{-\rho t} [\theta(\gamma X(t) + \eta R(t)) + \varepsilon_I - C_I(t) - \omega C_L(t)] dt \tag{25}$$

$$\max J_L^S = \int_0^\infty e^{-\rho t} [(1-\theta)(\gamma X(t) + \eta R(t)) + \varepsilon_L - (1-\omega) C_L(t) - C_R(t)] dt \tag{26}$$

The optimal revenue functions of the Internet enterprise and the logistics enterprise satisfy the following HJB equation:

$$\begin{aligned} \rho V_I = \max_{E_I} \{ & \theta(\gamma X(t) + \eta R(t)) + \varepsilon_I - (\tfrac{\mu_I}{2} + \tfrac{1}{k_I}) E_I^2(t) - w(\tfrac{\mu_L}{2} + \tfrac{1}{k_L}) E_L^2(t) + \\ & V'_{I1}(\lambda_I E_I(t) + \lambda_L E_L(t) - \delta X(t)) + V'_{I2}(\varphi M(t) - \psi R(t)) \} \end{aligned} \tag{27}$$

$$\begin{aligned} \rho V_L = \max_{E_L, M} \{ & \theta(\gamma X(t) + \eta R(t)) + \varepsilon_L - (1-w)(\tfrac{\mu_L}{2} + \tfrac{1}{k_L}) E_L^2(t) - \tfrac{\mu_R}{2} M^2(t) + \\ & V'_{L1}(\lambda_I E_I(t) + \lambda_L E_L(t) - \delta X(t)) + V'_{L2}(\varphi M(t) - \psi R(t)) \} \end{aligned} \tag{28}$$

Then, taking the partial derivatives with respect to E_L and M for Equation (28), and setting the value of the partial derivative to 0, the optimal solution of E_L and M can be obtained as follows:

$$E_L = \frac{\lambda_L V'_{L1}}{(1-w)(\mu_L + \frac{2}{k_L})}, M = \frac{\varphi V'_{L2}}{\mu_R} \tag{29}$$

Substituting Equation (29) into Equation (27), and then taking the partial derivatives of Equation (27) with respect to E_I and w, the optimal solution of E_I and w can be obtained as follows:

$$E_I = \frac{\lambda_I V'_{I1}}{(\mu_I + \frac{2}{k_I})}, w = \frac{2V'_{I1} - V'_{L1}}{2V'_{I1} + V'_{L1}} \tag{30}$$

Further substitute Equations (29) and (30) into Equations (27) and (28) and simplify as follows:

$$\rho V_I = \max\{(\theta\gamma - V'_{I1}\delta) X(t) + (\theta\eta - V'_{I2}\psi) R(t) + \frac{\lambda_I^2 (V'_{I1})^2}{2(\mu_I + \frac{2}{k_I})} + \frac{\lambda_L^2 (2V'_{I1} + V'_{L1})^2}{8(\mu_L + \frac{2}{k_L})} + \frac{\varphi^2 V'_{I2} V'_{L2}}{\mu_R} + \varepsilon_I \} \tag{31}$$

$$\begin{aligned} \rho V_L = \max\{ & ((1-\theta)\gamma - V'_{L1}\delta) X(t) + ((1-\theta)\eta - V'_{L2}\psi) R(t) + \\ & \tfrac{\lambda_L^2 V'_{L1}(2V'_{I1} + V'_{L1})}{4(\mu_L + \frac{2}{k_L})} + \tfrac{\lambda_I^2 V'_{I1} V'_{L1}}{(\mu_I + \frac{2}{k_I})} + \tfrac{\varphi^2 (V'_{L2})^2}{2\mu_R} + \varepsilon_L \} \end{aligned} \tag{32}$$

From Equations (31) and (32), it is known that the solution to the HJB equation is a linear function of two variables, X and R. Let

$$V_I^S = f_I^S X(t) + g_I^S R(t) + m_I^S; V_L^S = f_L^S X(t) + g_L^S R(t) + m_L^S \quad (33)$$

where the parameters in Equation (33) are constants except X and R. Taking partial derivatives of Equations (31) and (32) with respect to X and R, further set them to zero, and the parameter values of f_I^S, f_L^S, g_I^S, g_L^S, m_I^S, and m_L^S can be calculated as follows:

$$f_I^S = V'_{I1} = \frac{\theta\gamma}{\rho+\delta}, g_I^S = V'_{I2} = \frac{\theta\eta}{\rho+\psi}; f_L^S = V'_{L1} = \frac{(1-\theta)\gamma}{\rho+\delta}, g_L^S = V'_{L2} = \frac{(1-\theta)\eta}{\rho+\psi} \quad (34)$$

$$m_I^S = \frac{1}{\rho}\{\frac{\lambda_I^2\theta^2\gamma^2}{2(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{\lambda_L^2(1+\theta)^2\gamma^2}{8(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{\varphi^2\theta(1-\theta)\eta^2}{\mu_R(\rho+\psi)^2} + \varepsilon_I\} \quad (35)$$

$$m_L^S = \frac{1}{\rho}\{\frac{\lambda_L^2(1-\theta^2)\gamma^2}{4(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{\lambda_I^2(1-\theta)\theta\gamma^2}{(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{\varphi^2(1-\theta)^2\eta^2}{2\mu_R(\rho+\psi)^2} + \varepsilon_L\} \quad (36)$$

Substitute Equation (34) into Equations (29) and (30) as follows:

$$(E_I^{S^*}, E_L^{S^*}, M^{S^*}) = (\frac{\lambda_I k_I\theta\gamma}{(\mu_I k_I+2)(\rho+\delta)}, \frac{\lambda_L k_L(1+\theta)\gamma}{2(\mu_L k_L+2)(\rho+\delta)}, \frac{(1-\theta)\varphi\eta}{\mu_R(\rho+\psi)}) \quad (37)$$

$$w = \begin{cases} \frac{3\theta-1}{1+\theta}, \frac{1}{3} < \theta < 1 \\ 0, others \end{cases} \quad (38)$$

The optimal revenue functions of the Internet enterprise and the logistics enterprise can be expressed as follows:

$$V_I^S(t) = \frac{\theta\gamma}{\rho+\delta}X(t) + \frac{\theta\eta}{\rho+\psi}R(t) + \frac{1}{\rho}\{\frac{\lambda_I^2\theta^2\gamma^2}{2(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{\lambda_L^2(1+\theta)^2\gamma^2}{8(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{\theta(1-\theta)\varphi^2\eta^2}{\mu_R(\rho+\psi)^2} + \varepsilon_I\} \quad (39)$$

$$V_L^S(t) = \frac{(1-\theta)\gamma}{\rho+\delta}X(t) + \frac{(1-\theta)\eta}{\rho+\psi}R(t) + \frac{1}{\rho}\{\frac{(1-\theta^2)\lambda_L^2\gamma^2}{4(\mu_L+\frac{2}{k_L})(\rho+\delta)^2} + \frac{(1-\theta)\theta\lambda_I^2\gamma^2}{(\mu_I+\frac{2}{k_I})(\rho+\delta)^2} + \frac{(1-\theta)^2\varphi^2\eta^2}{2\mu_R(\rho+\psi)^2} + \varepsilon_L\} \quad (40)$$

Thus, the optimal total revenue function of both participating enterprises can be expressed as follows:

$$V_T^S(t) = \frac{\gamma}{\rho+\delta}X(t) + \frac{\eta}{\rho+\psi}R(t) + \frac{1}{\rho}\{\frac{(3-\theta)(1+\theta)\lambda_L^2\gamma^2}{8(\mu_L+\frac{2}{k_L})(\rho+\gamma)^2} + \frac{\theta(2-\theta)\lambda_I^2\gamma^2}{2(\mu_I+\frac{2}{k_I})(\rho+\gamma)^2} + \frac{(1-\theta^2)\varphi^2\eta^2}{2\mu_R(\rho+\psi)^2} + \varepsilon_I + \varepsilon_L\} \quad (41)$$

4.4. Comparison of Model Results under the Three Different Mechanisms

By comparing the optimal effort levels of the Internet enterprise and the logistics enterprise, the optimal marketing effort level of the logistics enterprise, the optimal revenues of both participating enterprises, and the total revenue for the intelligent upgrading of logistics under three mechanisms, the paper draws the following corollaries:

Corollary 1. *When* $\theta \in (\frac{1}{3}, 1), E_I^{C^*} > E_I^{S^*} = E_I^{N^*}$, $E_L^{C^*} > E_L^{S^*} = E_L^{N^*}$, $M^{C^*} > M^{S^*} = M^{N^*}$.

Proof. See Equations (42)–(47). □

$$E_I^{S^*} - E_I^{N^*} = \frac{\lambda_I k_I\theta\gamma}{(\rho+\delta)(k_I\mu_I+2)} - \frac{\lambda_I k_I\theta\gamma}{(\rho+\delta)(k_I\mu_I+2)} = 0 \quad (42)$$

$$E_I^{C^*} - E_I^{S^*} = \frac{(1-\theta)\lambda_I k_I \gamma}{(\mu_I k_I + 2)(\rho + \delta)} > 0 \tag{43}$$

$$E_L^{S^*} - E_L^{N^*} = \frac{\lambda_L k_L (1+\theta)\gamma}{2(\mu_L k_L + 2)(\rho + \delta)} - \frac{\lambda_L k_L (1-\theta)\gamma}{(\rho+\delta)(k_L \mu_L + 2)} = \frac{\lambda_L k_L (3\theta - 1)\gamma}{2(\mu_L k_L + 2)(\rho + \delta)} > 0 \tag{44}$$

$$E_L^{C^*} - E_L^{S^*} = \frac{\lambda_L k_L \gamma}{(\mu_L k_L + 2)(\rho + \delta)} - \frac{\lambda_L k_L (1+\theta)\gamma}{2(\mu_L k_L + 2)(\rho + \delta)} = \frac{\lambda_L k_L (1-\theta)\gamma}{2(\mu_L k_L + 2)(\rho + \delta)} > 0 \tag{45}$$

$$M^{S^*} - M^{N^*} = \frac{(1-\theta)\varphi\eta}{\mu_R(\rho + \psi)} - \frac{(1-\theta)\varphi\eta}{\mu_R(\rho + \psi)} = 0 \tag{46}$$

$$M^{C^*} - M^{S^*} = \frac{\varphi\eta}{\mu_R(\rho + \psi)} - \frac{(1-\theta)\varphi\eta}{\mu_R(\rho + \psi)} = \frac{\theta\varphi\eta}{\mu_R(\rho + \psi)} > 0 \tag{47}$$

Corollary 1 demonstrates that under the cooperative mechanism, the Internet enterprise and logistics enterprise exert maximum effort to promote the intelligent upgrading of logistics. Notably, the logistics enterprise also invests the maximum marketing cost to improve the goodwill of intelligent logistics. In contrast to the non-cooperative mechanism, the cost allowance provided by the Internet enterprise can incentivize the logistics enterprise to make more effort towards the intelligentization of logistics, while the effort level by the Internet enterprises remains unchanged.

Corollary 2. *When* $\theta \in (\frac{1}{3}, 1), V_I^S > V_I^N, V_L^S > V_L^N, V_T^C > V_T^S > V_T^N$.

Proof. See Equations (48)–(51). □

$$V_I^S - V_I^N = \frac{(1-3\theta)^2 k_L \lambda_L^2 \gamma^2}{8(\mu_L k_L + 2)(\rho + \delta)^2 \rho} > 0 \tag{48}$$

$$V_L^S - V_L^N = \frac{(3\theta - 1)(1-\theta) k_L \lambda_L^2 \gamma^2}{4(\mu_L k_L + 2)(\rho + \delta)^2 \rho} > 0 \tag{49}$$

$$V_T^S - V_T^N = \frac{(3\theta - 1)(1+\theta) k_L \lambda_L^2 \gamma^2}{8(\mu_L k_L + 2)(\rho + \delta)^2 \rho} > 0 \tag{50}$$

$$V_T^C - V_T^S = \frac{(1-\theta)^2 k_I \lambda_I^2 \gamma^2}{2(\mu_I k_I + 2)(\rho + \delta)^2 \rho} + \frac{(1-\theta)^2 k_L \lambda_L^2 \gamma^2}{8(\mu_L k_L + 2)(\rho + \delta)^2 \rho} + \frac{\theta^2 \varphi^2 \eta^2}{2\mu_R(\rho + \psi)^2 \rho} > 0 \tag{51}$$

Corollary 2 demonstrates that under the cost-sharing mechanism, the optimal revenues accrued by the Internet enterprise and the logistics enterprise through the intelligent upgrading of logistics surpass that of the non-cooperative mechanism. Specifically, when the Internet enterprise provides the cost allowance for the logistics enterprise, the total revenue can be enhanced, leading to a Pareto improvement. Furthermore, under the cooperative mechanism, the total revenue derived from the intelligent upgrading of logistics by both participating enterprises exceeds that of the other mechanisms, thereby achieving Pareto optimality.

Corollary 3. *When the Internet enterprise provides a cost allowance to the logistics enterprise, the logistics enterprise is willing to put more effort into the intelligent upgrading of logistics, which ultimately enhances the intelligent level of logistics. Under the cooperative mechanism, the intelligent* *level of logistics is the highest among the three mechanisms. Meanwhile, the marketing cost of the logistics enterprise aimed at increasing the goodwill of the intelligent logistics is the highest.*

Proof. Solving the kinematics Equation (2) with respect to $X(t)$, the optimal trajectory of the intelligent level of logistics can be obtained as follows:

$$X(t) = \Omega_X^* + (X_0 - \Omega_X^*)e^{-\delta t}, \Omega_X^* = \frac{\lambda_I E_I^* + \lambda_L E_L^*}{\delta} \tag{52}$$

It can be derived from Corollary 1 that $\frac{\lambda_I E_I^{C^*} + \lambda_L E_L^{C^*}}{\delta} > \frac{\lambda_I E_I^{S^*} + \lambda_L E_L^{S^*}}{\delta} > \frac{\lambda_I E_I^{N^*} + \lambda_L E_L^{N}}{\delta}$, i.e., $\Omega_X^{C^*} > \Omega_X^{S^*} > \Omega_X^{N^*}$. Then, take the partial derivative of $X(t)$ with respect to Ω_X^* as follows:

$$\frac{dX}{d\Omega_X^*} = 1 - e^{-\delta t} > 0 \tag{53}$$

It can be inferred that $X(t)$ is an increasing function with respect to Ω_x^*. Further solving the kinematics Equation (3) with respect to $R(t)$, the optimal trajectory of the goowill of intelligent logistics can be obtained as follows:

$$R(t) = \Omega_R^* + (R_0 - \Omega_R^*)e^{-\psi t}, \Omega_R^* = \frac{\varphi M^*}{\psi} \tag{54}$$

Similarly, it can be derived from Corollary 1 that $\frac{\varphi M^{C^*}}{\psi} > \frac{\varphi M^{S^*}}{\psi} = \frac{\varphi M^{N^*}}{\psi}$, i.e., $\Omega_R^{C^*} > \Omega_R^{S^*} > \Omega_R^{N^*}$. Then, take the partial derivative of $R(t)$ with respect to Ω_R^* as follows:

$$\frac{dR}{d\Omega_R^*} = 1 - e^{-\psi t} > 0 \tag{55}$$

The proof is complete. □

It can also be inferred that $X(t)$ is an increasing function with respect to Ω_R^*.

Corollary 4. *The cost-sharing ratio w is an increasing function of the revenue distribution coefficient θ.*

Proof. When $\theta \in (\frac{1}{3}, 1)$, the derivative of w with respect to θ can be obtained as follows:

$$\frac{\partial w}{\partial \theta} = \frac{4}{(1+\theta)^2} > 0, \theta \in (\frac{1}{3}, 1) \tag{56}$$

The proof is complete. □

It means that, as the revenue distribution coefficient of the Internet enterprise increases, the proportion of cost allowance to the logistics enterprise increases as well, which can effectively relieve the cost burden of the logistics enterprise for the intelligent upgrading of logistics. Furthermore, Corollary 4 also implies that economic benefits serve as the key incentives for Internet enterprises to support the intelligent transformation of traditional logistics enterprises with highly technical resources and consulting services about the intelligent operation. According to the model assumptions presented in this paper, the Internet enterprise is inclined to subsidize the logistics enterprise when the revenue distributed to it surpasses a specific proportion of the total revenue ($\theta > \frac{1}{3}$).

5. Numerical Simulation and Sensitivity Analysis

Section 4.4 analyzed and compared the differences in optimal effort levels, optimal revenues, the intelligent level of logistics, and the goodwill of intelligent logistics for the Internet enterprise and the logistics enterprise under three mechanisms. In this section, the software Python 3.10 is used for numerical simulation to verify the validity of the differential game models and further observe the effect of the key parameters on the total revenue on the intelligent upgrading of logistics. The paper set the model parameters properly by referring to [46] and considering the feasibility of dynamic evolution for the differential game model: $X(0) = X_0 = 1, R(0) = R_0 = 0, \mu_I = 0.3, \mu_L = 0.4, \mu_R = 0.3, k_I = 10, k_L = 8, \lambda_I = 0.7, \lambda_L = 0.6, \delta = 0.3, \varphi = 0.7, \psi = 0.5, \gamma = 0.7, \eta = 0.5, \theta = 0.6, \varepsilon_I = 2, \varepsilon_L = 1, \rho = 0.1$.

5.1. Numerical Simulation under Three Mechanisms

As depicted in Figure 2, the intelligent level of logistics increases over time and eventually stabilizes, which is consistent with Corollary 3. The cost incentive provided by the Internet enterprise is conducive to enhancing the intelligent level of logistics. Additionally, the intelligent level of logistics is highest under the cooperative mechanism. It also suggests that the Internet enterprise and the logistics enterprise should maintain long-term and in-depth collaboration based on the intelligent upgrading of logistics, which ultimately gains better feedback.

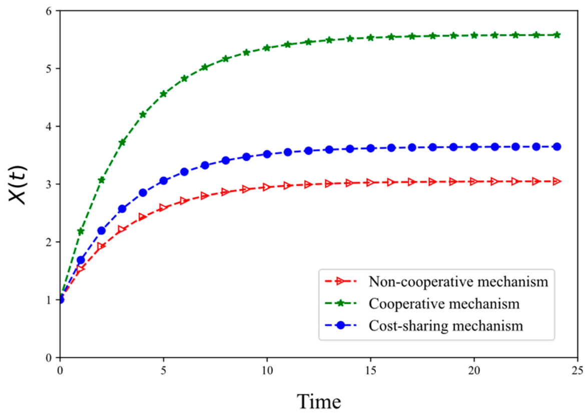


Figure 2. Comparison of the intelligent level of logistics under three mechanisms.

As shown in Figure 3, the goodwill of intelligent logistics under the cooperative mechanism is notably higher than the goodwill of intelligent logistics level under the non-cooperative mechanism and the cost-sharing mechanism, and the goodwill of intelligent logistics is the same at any time point for the latter two collaborative mechanisms. It occurs because participating enterprises devote their efforts to maximizing collective revenue by jointly determining and sharing the advertising and marketing costs. Under the cooperative mechanism, the promoting cost of intelligent logistics can also be attributed to the internal transfer of resources among the participating enterprises, which alleviates the cost constraints of the logistics enterprise.

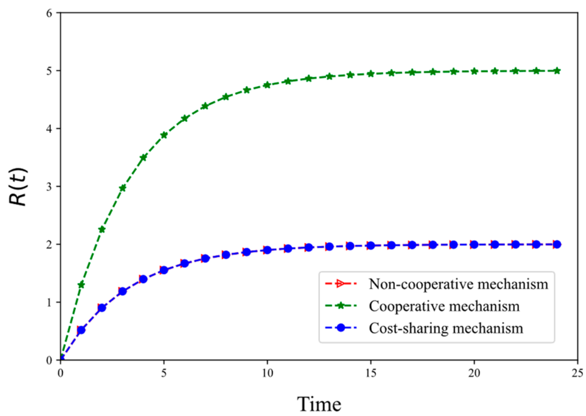


Figure 3. Comparison of the goodwill of intelligent logistics under three mechanisms.

Figure 4a and Figure 4b respectively illustrate the optimal revenues obtained by the Internet enterprise I and the logistics enterprise L at different time points from the intelligent upgrading of logistics under the non-cooperative mechanism and the cost-sharing mechanism. Figure 5 reflects the total revenues generated by the intelligent upgrading of logistics at different time points under three collaborative mechanisms.

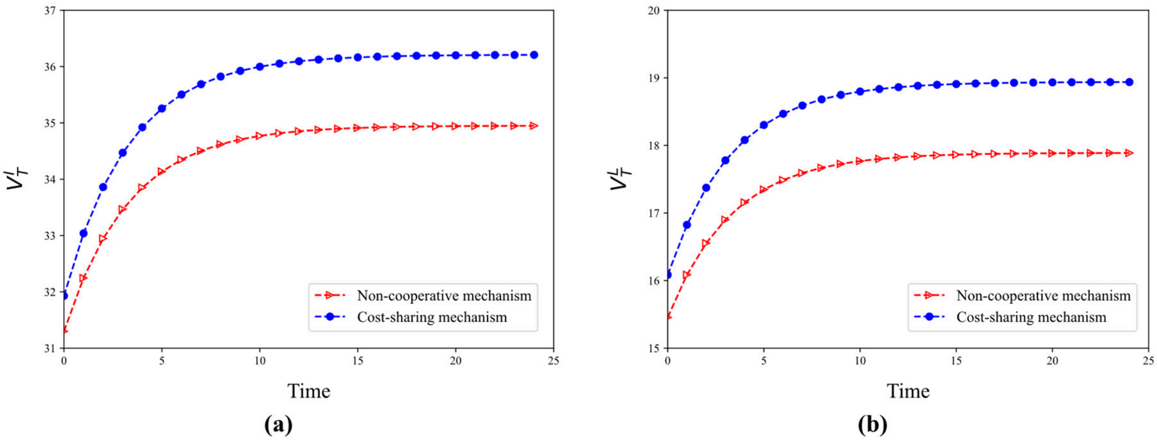


Figure 4. Optimal revenues of the Internet enterprise and the logistics enterprise.

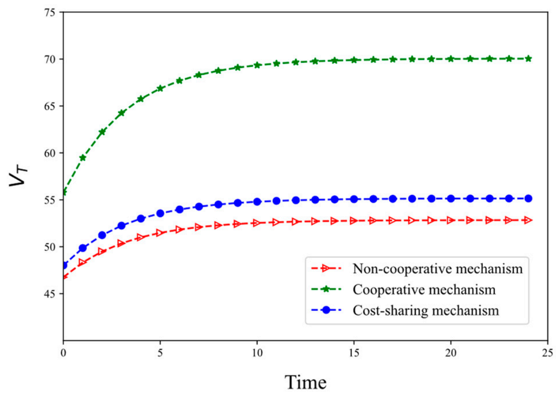


Figure 5. Comparison of the total revenue under three mechanisms.

As shown in Figures 4 and 5, the optimal revenue obtained by the Internet enterprises and the logistics enterprise under the cost-sharing mechanism is higher than that under the non-cooperative mechanism at any time. The total revenue of participating enterprises reaches its highest under the cooperative mechanism, which verifies the conclusions drawn from Corollary 2. Furthermore, the optimal revenue of both participating enterprises increases over time and eventually stabilizes. The above simulation results indicate the Internet enterprise provides the cost allowance for the logistics enterprise, which can effectively motivate the logistics enterprise to construct the intelligent logistics, thereby improving the total revenue from the intelligentization of logistics. Meanwhile, the in-depth cooperative mechanism between the Internet enterprise and the logistics enterprise, including resource sharing and technical support, is highly effective in improving the total revenue from the intelligent upgrading of logistics.

5.2. The Effect of Key Parameters on the Numerical Simulation

As depicted in Figure 6, though the total revenue still increases over time under the cost-sharing mechanism and the non-cooperative mechanism, the total revenue decreases gradually as the revenue distribution coefficient θ rises under the non-cooperative mechanism. In contrast, under the cost-sharing mechanism, the total revenue still increases significantly as θ increases, achieving Pareto improvement. Referring to Section 4, it can be seen that a higher revenue distribution coefficient indicates that the Internet enterprise yields a greater share of the total revenue from the intelligent upgrading of logistics. Under the non-cooperative mechanism, since $\frac{\partial E_L^*}{\partial \theta} < 0$ and $\frac{(\partial R^*)}{\partial \theta} < 0$, the level of effort and marketing cost of the logistics enterprise decrease as θ increases. This can be attributed to the fact that the limited collaboration between the logistics enterprise and the Internet enterprise is primarily maintained through long-term cooperation based on commodity or service trade to reduce the cost of accessing information and operating. Therefore, the total revenue of the intelligent upgrading of logistics remains at a low level, and the logistics enterprise is not satisfied with the collaborative outcome of "low revenue–low distribution". However, since $\frac{\partial E_L^*}{\partial \theta} > 0$, the effort level of the logistics enterprise will increase with θ under the cost-sharing mechanism. Meanwhile, the cost-sharing ratio of the Internet enterprise will also increase. For the logistics enterprise, the marginal revenue gained from the increase in the cost-sharing ratio w will exceed the loss of marginal revenue due to the decrease in the revenue distribution coefficient $(1-\theta)$. Consequently, compared to the non-cooperative scenario, the logistics enterprise will make more effort in the establishment of intelligent logistics.

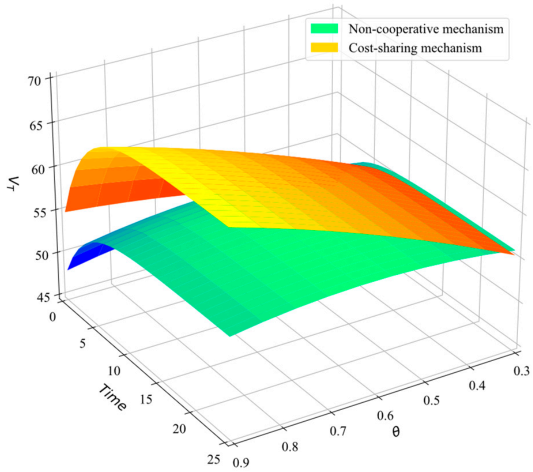


Figure 6. The effect of θ and *time* on V_T.

Figure 7 demonstrates the impact of the marginal impact coefficients λ_I and λ_L of the intelligent upgrading of logistics on the total revenue, and Figure 8 further illustrates the impact of the marginal impact coefficients λ_I and λ_L on the differences in total revenue Δ_{V_T} under two distinct mechanisms.

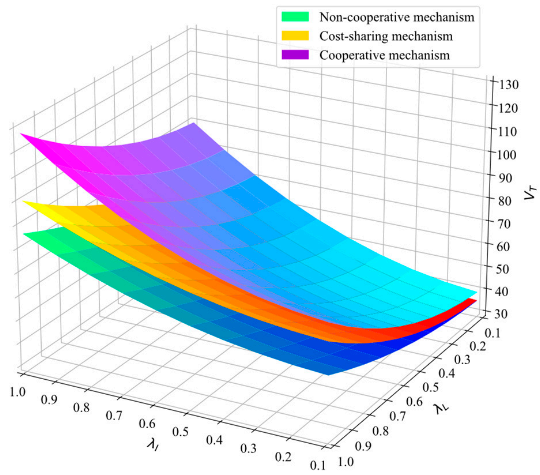


Figure 7. The effect of λ_I and λ_L on V_T.

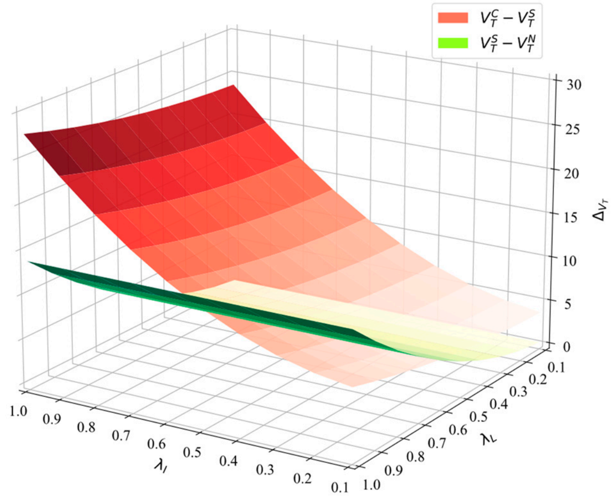


Figure 8. The effect of λ_I and λ_L on Δ_{V_T}.

Under three collaborative mechanisms, the increase of λ_I and λ_L improves the overall revenue of the intelligent upgrading of logistics. Referring to Corollary 2, since $\frac{\partial V_T^C}{\partial \lambda_{I,L}} > \frac{\partial V_T^S}{\partial \lambda_{I,L}}$ and $\frac{\partial V_T^S}{\partial \lambda_L} > \frac{\partial V_T^N}{\partial \lambda_L}$, the efficiency of the overall revenue enhancement is highest under the cooperative mechanism, followed by the cost-sharing mechanism, and weakest under the non-cooperative mechanism, as can be seen in Figure 8. When λ_I and λ_L reach the highest level, the total revenue of the intelligentization of logistics is also at the maximum. The marginal impact coefficient is influenced by both internal factors, including the level of informatization, R&D capabilities, and enterprise scale, and external factors such as technical capability and business environment. In practice, both participating enterprises are susceptible to a decline in intelligent capability, which could diminish the intelligent level of logistics and total revenue. Consequently, they might be unwilling to develop intelligent logistics in the long term. Nevertheless, the Internet enterprise and the logistics enterprise can still obtain high revenue from the intelligent upgrading of logistics under the cooperative mechanism, which will make intelligent logistics sustainable, especially when the revenues created by intelligent logistics exceed the development costs.

Figure 9 demonstrates the impact of the goodwill coefficient of intelligent logistics on the total revenue. As φ increases, the total revenue from the intelligent upgrading of logistics increases under three mechanisms. The goodwill coefficient φ reflects the extent of customer preference for intelligent logistics services. Intelligent logistics not only reduces operating costs through technological empowerment, but also offers value-added customer services, such as precise distribution and a quick response, to create marketing value. The derivation of Equations (49) and (50) with respect to φ shows that $\frac{\partial V_T^S}{\partial \varphi} = \frac{\partial V_T^N}{\partial \varphi}$, $\frac{\partial V_T^C}{\partial \varphi} > \frac{\partial V_T^S}{\partial \varphi}$, indicating that the marginal revenue increased by the increase in φ is optimal under the cooperative mechanism, as can be seen in Figure 10, and the logistics enterprise will aim at maximizing the total revenue to enhance the marketing investment in intelligent logistics. In contrast, under the cost-sharing mechanism, the Internet enterprise is under no obligation to share the cost with the logistics enterprise for the publicity and marketing of intelligent logistics, and the marketing effort made by the logistics enterprise is equal to that in the non-cooperative mechanism. This means that a low level of the goodwill of intelligent logistics can only bring limited revenue for the participating enterprises. Referring to Equation (37), $\frac{\partial M^{N^*}}{\partial \theta} = \frac{\partial M^{S^*}}{\partial \theta} = -\frac{\varphi\eta}{\mu_R(\rho+\psi)} < 0$, the revenue distribution coefficient of the logistics enterprises $(1-\theta)$ will negatively affect the marketing effort, resulting in the impairment of the goodwill of intelligent logistics. At the preliminary stage of constructing intelligent logistics, disparities in technical endowments and financial resources exist between the Internet enterprise and the logistics enterprise.

Both participating enterprises are inclined to maintain limited cooperation to mitigate potential risks. Implementing a rational revenue distribution mechanism will encourage the logistics enterprise to augment its marketing investment, thereby enhancing the goodwill of intelligent logistics and fostering customer resource accumulation.

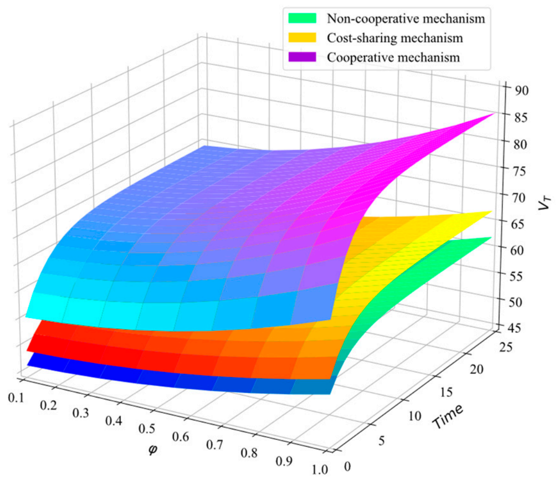


Figure 9. The effect of φ and *time* on V_T.

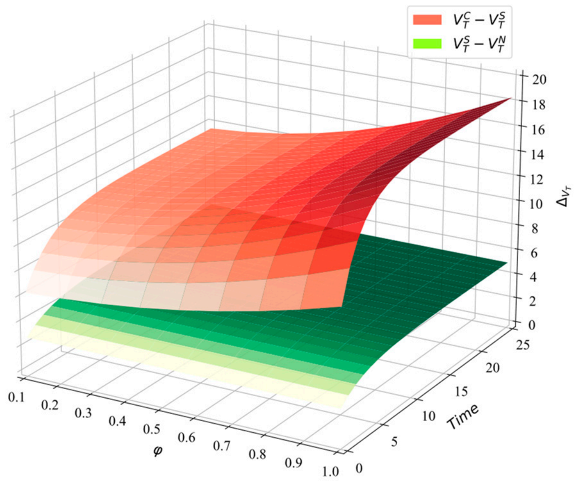
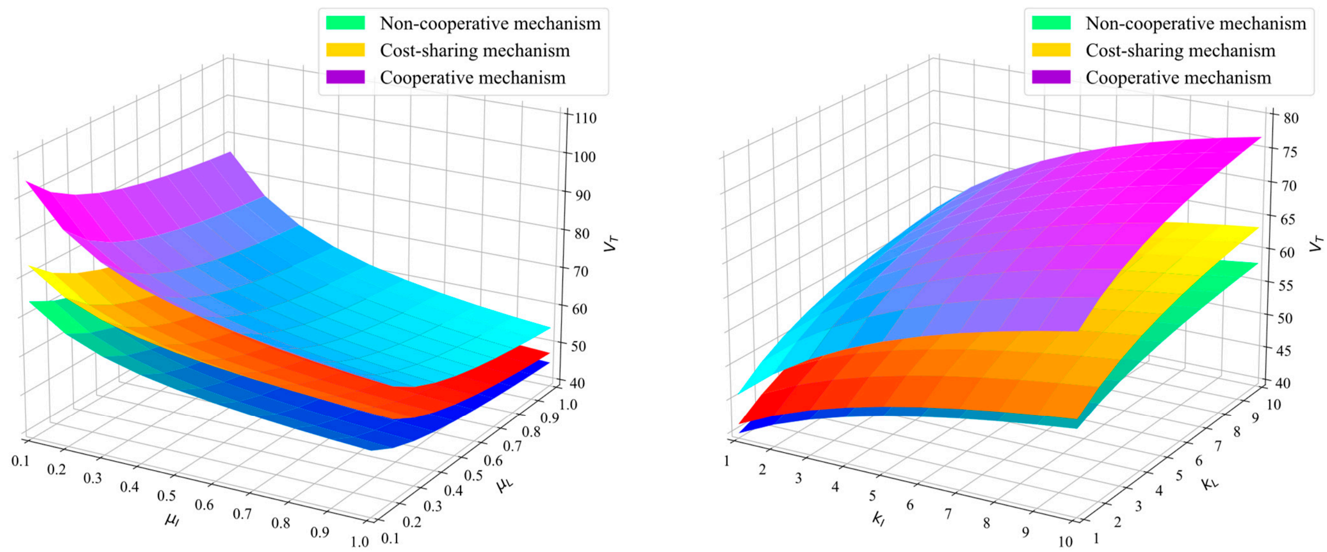


Figure 10. The effect of φ and *time* on Δ_{V_T}.

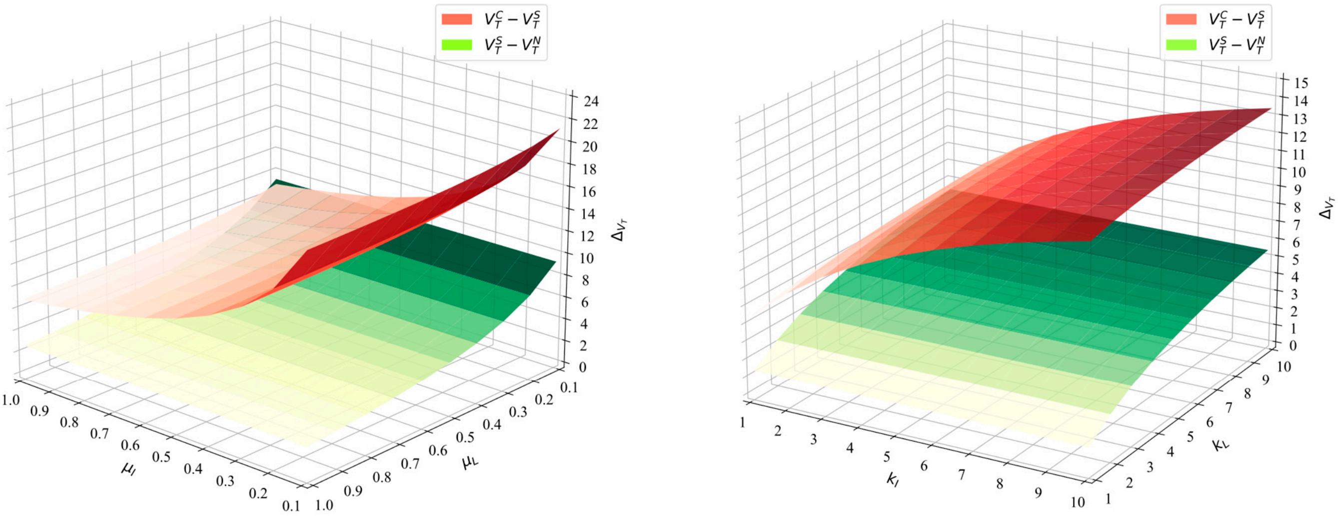
Figure 11a demonstrates the impact of cost coefficient μ_I and μ_L on the total revenue of participating enterprises under three collaborative mechanisms, and Figure 12a further illustrates the impact of the cost coefficients μ_I and μ_L on the differences in total revenue under different collaborative mechanisms. Under three different mechanisms, the total revenue gradually decreases as μ_I and μ_L increases. The derivation of Equation (50) with respect to μ_I and μ_L, respectively, shows that $\frac{\partial V_T^S}{\partial \mu_I} = \frac{\partial V_T^N}{\partial \mu_I}$, and $\frac{\partial V_T^S}{\partial \mu_L} < \frac{\partial V_T^N}{\partial \mu_L} < 0$, and the magnitude of the detrimental effect of the cost coefficient μ_L on the total revenue is greater under the cost-sharing mechanism than under the non-cooperative mechanism, as can be seen in Figure 12a. This suggests that when the Internet enterprise provides a special cost allowance for the logistics enterprise, the latter can proactively implement measures such as providing employee skill training, establishing incentive systems, and fostering cross-departmental collaboration to enhance cost management capabilities, which further improve the intelligent level of logistics and increase total revenue. Then, taking the derivation of Equation (51) with respect to μ_I and μ_L, respectively, shows that $\frac{\partial V_T^C}{\partial \mu_I} < \frac{\partial V_T^S}{\partial \mu_I} < 0$ and $\frac{\partial V_T^C}{\partial \mu_L} < \frac{\partial V_T^S}{\partial \mu_L} < 0$, as can be seen in Figure 12a. The cost coefficients μ_I and μ_L

exert a greater detrimental effect on the total revenue under the cooperative mechanism than under the cost-sharing mechanism. It reveals that participating enterprises can enhance their cost conversion efficiency through resilient cooperation, thereby improving the total revenue.



(a) **(b)**

Figure 11. The effect of μ_I, μ_L and k_I, k_L on V_T.



(a) **(b)**

Figure 12. The effect of μ_I, μ_L and k_I, k_L on Δ_{V_T}.

This study also examines the impact of variations in technology adaptation coefficients k_I and k_L on the total revenue under three different mechanisms, as depicted in Figure 11b. Under three different mechanisms, the total revenue from the intelligent upgrading of logistics gradually improves as k_I and k_L increases. Similarly, take the derivatives of Equations (50) and (51) with respect to k_I and k_L, respectively. The following conclusions can be drawn: under the cost-sharing mechanism, the positive impact of the technology adaptation coefficient k_L on the total revenue is greater than that under the non-cooperative mechanism. Furthermore, the positive impact of the technology adaptation coefficients k_I and k_L on the total revenue is greater under the cooperative mechanism compared to the cost-sharing mechanism, as can be seen in Figure 12b. Technology adaptability denotes the capacity to assist enterprises to swiftly integrate and internalize intelligent technologies, thereby expediting the intelligent transformation for the logistics enterprise. During this transformation, the participating enterprises ought to vigilantly track the evolutionary trend of the intelligent sector, promptly adopt advanced intelligent technologies, create a knowledge repository, consolidate and reallocate external technical knowledge with internal innovative resources, expand their original knowledge base, advance technological standardization, and bolster technological adaptability.

6. Managerial Implications

The above findings have the following managerial implications for enterprises collaboration in the intelligent upgrading of logistics:

(1) Participating enterprises should formulate a multi-dimensional revenue distribution mechanism and cost-sharing mechanism on the basis of their own technological contribution, financial support, and risk-taking level, and strengthen their long-term trust relationship by entering into project cooperation agreements, engaging in joint investments, and engaging in cross ownership, which can ensure the unity of purpose between participating enterprises in intelligent logistics development.

(2) On the one hand, Internet enterprises should create innovative capacity to develop software and devices for intelligent logistics and, through technological exchanges and the "opened and shared laboratory" project, should provide R&D resources to logistics enterprises with lower technological endowments to improve the synchronization of intelligent development. On the other hand, logistics enterprises should pay more attention to the advanced science of the logistics industry, proactively expanding the application of emerging technologies, such as Smart WMS and Smart TMS. Compared with the traditional logistics management system, the smart logistics system utilizes machine learning and artificial intelligence algorithms, enabling it to perform inventory forecasting and intelligent path planning. These functional modules allow for a more accurate and efficient process planning of warehouse operations.

(3) Logistics enterprises should establish an effective information-sharing mechanism with Internet enterprises and align the intelligent technology and equipment from internet enterprises with suitable application scenarios. In addition, participating enterprises should cultivate research-oriented and application-oriented talents in intelligent logistics. They can support conducive resources for logistics professionals to focus on their research by leveraging the resources of universities and research institutes. Meanwhile, they should attach much importance to conducting training programs involving comprehensive intelligent logistics skills for employees and developing engaging teaching cases based on regular operational experiences in intelligent logistics. These practices enhance the compatibility of intelligent technologies within logistics enterprises.

(4) Participating enterprises should collaborate to develop business modules that encompass precise distribution, quick response, and online feedback mechanisms, thereby enhancing the marketing competitive advantages of intelligent logistics. This not only meets the experiential consumption needs of customers but also enhances service value.

(5) An evaluation system for the intelligentization of logistics should be established to monitor and accurately assess the intelligent level of logistics and revenue in real time, identifying key elements for the intelligent upgrading of logistics. This evaluation system will provide valuable insights for subsequent practices aimed at the intelligent upgrading of logistics.

7. Conclusions and Research Limitations

In light of complex business environments, intense market competition, and heightened quality demands from customers regarding logistics services, logistics enterprises must reform the traditional business model and embrace intelligent transformation. They must reassess their fundamental business essence by acquiring and integrating information to nurture high-value and distinctive logistics services. This objective can be accomplished by enhancing intelligent capabilities through scientific and technological innovation, effective human resources management, and strategic partnerships. This necessitates the adherence to principles of cooperation and resource sharing, promoting deep integration between the information industry and logistics industries. The utilization of information technology and advanced intelligent logistics equipment is essential for achieving intelligent operations, resource sharing, and multifaceted development in logistics. These enhancements are beneficial for improving logistics services, reducing operational costs, and fostering sustainable multi-dimensional growth. This research, rooted in differential game theory, explores collaborative strategies and revenue transformation mechanisms between an Internet enterprise and a logistics enterprise for the intelligent upgrading of logistics. By solving the Hamilton–Jacobi–Bellman equations under the non-cooperative mechanism, the cost-sharing mechanism and the cooperative mechanism, this study determines the optimal effort levels for the Internet enterprise and the logistics enterprise, the marketing cost for forming the goodwill of intelligent logistics, and the optimal revenues derived from the intelligent upgrading of logistics. The following conclusions are obtained by comparing the equilibrium solutions and simulation results under the three collaborative mechanisms:

(1) The cost-sharing mechanism and the cooperative mechanism can motivate participating enterprises to improve their own efforts for the intelligent upgrading of logistics and eventually increase the revenue of collaboration. Under the cooperative mechanism, the efforts made by the Internet enterprise and the logistics enterprise and the advertising and marketing cost of the logistics enterprise are the highest, with the result that the level of intelligent upgrading of logistics and the goodwill of intelligent logistics both reach the highest level. Under the cost-sharing mechanism, the higher revenue distribution ratio can persuade the Internet enterprise to provide more cost allowance to the logistics enterprise.
(2) Participating enterprises can increase the revenue by creating and improving internal and external conditions conducive to the intelligent upgrading of logistics. This includes enhancing the enterprise's capacity for intelligent innovation and cost management efficiency, as well as cultivating customer preference for intelligent logistics services.
(3) Under the non-cooperative mechanism, a lower revenue distribution ratio diminishes the willingness of logistics enterprises to make an effort in the intelligent upgrading of logistics, which is not conducive to the improvement of total revenue. Conversely, when internet enterprises extend a cost allowance to the logistics enterprises in accordance with the revenue distribution, it can effectively alleviate the revenue competition between them. At that time, as the revenue sharing ratio increases, the more effort logistics enterprises put into the intelligent upgrading of logistics, which still increases total revenue. Under the cost-sharing mechanism and the non-cooperative mechanism, a diminished revenue sharing ratio can discourage the logistics enterprise from investing more advertising and marketing costs on intelligent logistics, which ultimately weakens the goodwill of intelligent logistics and undermines the total revenue.

There are still many limitations in this research: Firstly, the model assumption is relatively idealized, failing to account for the involvement of multiple logistics enterprises and Internet enterprises in the intelligent upgrading of logistics. Future research could employ an evolutionary game model to elucidate the strategic behavior of participating enterprises. Secondly, it cannot be ignored that other essential conditions can also constrain the subject enterprise cooperation in the intelligent upgrading of logistics, including data security [47] and the pricing of intelligent logistics services. Additionally, government involvement plays a crucial role in facilitating the sustainable development of the logistics industry [48]. Presently, the government supports intelligent logistics [49] through establishing the standard system for intelligent logistics, infrastructure construction, and preferential tax policies. Subsequent research might consider the government as a collaborative agent and explore how government regulation and subsidy policy influence the collaborative decisions of participating enterprises.

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