

Article

Reciprocal Symbiosis Modes of Collaborative Work Safety Governance in Sustainable Industrial Parks

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Abstract

From the perspective of symbiosis theory, collaborative work safety governance in industrial parks can be understood as a dynamic multi-actor symbiotic system jointly composed of the park management committee, leading enterprises, and small and medium-sized enterprises. To examine how reciprocal symbiosis among multiple actors affects system-level safety performance and sustainable operation, this study develops a differential game model in which the work safety level of the industrial park evolves dynamically over time. The model comparatively analyzes the work safety efforts, discounted payoffs of symbiotic units, and the overall work safety level of the park under different decision-making mechanisms and reciprocal symbiosis modes. The results show that: (1) under the leading-enterprise-dominated mode, as the coefficient of work safety resource sharing increases, the overall work safety level of the park correspondingly improves; however, once this coefficient exceeds a certain threshold, it becomes unfavorable to the further growth of the leading enterprise's own benefit; (2) under the park-management-committee-led mode, as the cost-sharing coefficient increases, the overall work safety level of the park continues to improve, but an excessively high cost-sharing coefficient weakens the incentive for the park management committee to increase its benefit; and (3) under certain conditions, the leading-enterprise-dominated mode, the park-management-committee-led mode, and the deep collaboration mode can all improve both the park's work safety level and the discounted payoffs of symbiotic units, but the deep collaboration mode performs best in enhancing the overall work safety level and the total system payoff. Compared with the park-management-committee-led mode, the leading-enterprise-dominated mode is more sensitive in its impact on the total payoff of the industrial park. These findings indicate that sustainable work safety improvement in industrial parks cannot rely solely on increasing governance inputs or on the actions of a single actor. Instead, it requires a system-wide balance among safety performance, economic efficiency, resource-sharing sustainability, and the long-term stability of collaborative relationships. The study provides a system-oriented theoretical basis for optimizing reciprocal symbiosis mechanisms and promoting the sustainable development of industrial parks.



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1. Introduction

Industrial parks (hereinafter referred to as “parks”), as important carriers of regional economic development, have become major engines for promoting industrial transforma-

tion and upgrading as well as regional economic growth [1–3]. Owing to their distinctive agglomeration effects, parks attract leading enterprises with strong brand influence, market position, and resource advantages. Relying on such advantages, these leading enterprises further attract a large number of small and medium-sized enterprises related to their industrial chains (hereinafter referred to as “park enterprises”), gradually forming an industrial organizational structure characterized by division of labor and cooperation, resource complementarity, and network linkages [4,5]. Therefore, an industrial park is not merely a spatial concentration of enterprises, but a complex socio-technical-economic system in which multiple actors, resources, risks, and interests are closely interconnected.

With the continuous advancement of industrial upgrading, the collaborative linkages and symbiotic evolution among actors within parks have become increasingly prominent. However, while developing rapidly, parks are also facing increasingly complex challenges in work safety governance. On the one hand, the high degree of interdependence and risk transmission among enterprises within parks makes local accidents highly likely to escalate into systemic crises [6,7], which not only affect the normal production and operation of other non-accident enterprises in the park, but may also trigger environmental pollution, community disturbances, and broader social risks, thereby causing severe casualties, property losses, and negative social impacts [8,9]. On the other hand, work safety investment is characterized by obvious upfront input requirements, long-term commitment, and indirect returns, whereas market actors tend to place greater emphasis on short-term economic gains. This makes park work safety governance prone to practical dilemmas such as fragmented responsibilities, insufficient investment, and inefficient collaboration [10,11]. Therefore, how to improve the work safety level of parks while ensuring economic performance, reducing the systemic losses and external risks caused by accidents, and enhancing the sustainable operational capacity of industrial parks has become an important issue that urgently needs to be addressed in park governance.

Symbiosis theory emphasizes that heterogeneous actors can achieve the dynamic balance and sustainable development of a system as a whole through resource sharing, functional coordination, and benefit linkage, and it has been widely applied in fields such as society, economics, and management [12,13]. From the perspective of symbiosis theory, collaborative work safety governance in industrial parks can be regarded as a dynamic symbiotic system jointly composed of the park management committee, leading enterprises, and small and medium-sized enterprises within the park. These actors are not isolated decision makers, but interdependent symbiotic units whose safety efforts, resource inputs, and payoff outcomes jointly shape the dynamic evolution of the park’s overall work safety level.

Specifically, the park management committee, as the actor responsible for institutional supply and rule coordination, serves as a “provider of work safety rules” through safety access control, standard formulation, and routine management; leading enterprises, by virtue of their advantages in technology, equipment, managerial experience, and market position, act as “empowering actors for collaborative work safety governance” through resource sharing, demonstration effects, and chain-leader constraints; and small and medium-sized enterprises in the park, under work safety requirements, enhance their operational stability and competitiveness through collaborative interactions with chain-leading enterprises and park governance actors. The park management committee, leading enterprises, and park enterprises form the symbiotic interface of the park symbiotic system through interactions such as work safety policies, data sharing on work safety information-sharing platforms, and the embedding of safety clauses. Their patterns of interaction, realized through mechanisms such as policy transmission, information sharing, standard embedding, and collaborative management, constitute the symbiotic modes of the park work

safety symbiotic system, while external institutions, market conditions, and risk scenarios jointly form the symbiotic environment. Through these interactions, safety resources, governance responsibilities, costs, and benefits continuously flow and are redistributed among the three actors, generating feedback effects that influence both the work safety performance and the operational sustainability of the park system.

It should be noted that the symbiotic mode is the core of the operation of a symbiotic system, because it not only determines the internal mechanisms of resource allocation and benefit distribution, but also affects the stability of cooperation among symbiotic units and the operational efficiency of the system [14]. Among different symbiotic modes, the reciprocal symbiosis mode can reduce conflicts of interest among symbiotic units and is regarded as the most efficient and stable mode for sustaining a symbiotic system [15]. Therefore, in the context of the sustainable development of industrial parks, it is of considerable theoretical and practical significance to fully consider the interest relationships and collaborative mechanisms among participating actors, including the park management committee, leading enterprises, and park enterprises, and to explore reciprocal symbiosis modes that can simultaneously improve the park's work safety level, enhance the payoffs of actors within the symbiotic system, and promote the sustained and stable operation of the park.

2. Literature Review

2.1. Research on the Collaborative Development of Industrial Parks

The development of industrial parks is essentially a process of continuous interaction among multiple actors, ongoing resource reconfiguration, and the progressive deepening of collaborative relationships. Existing studies on the collaborative development of industrial parks have mainly examined this issue from the perspectives of industrial agglomeration and industrial-chain cooperation. On the one hand, the foundation of collaborative development in industrial parks lies in the division of labor and cooperative relationships formed under conditions of spatial agglomeration [16,17]. Driven by geographical proximity, industrial linkages, and factor sharing, firms within industrial parks gradually form organizational networks characterized by specialized division of labor and supporting cooperation [18,19]. In particular, leading enterprises, by virtue of their technological, financial, branding, and market advantages, often occupy a central position in industrial-chain integration, resource organization, and rule shaping, and promote the development of small and medium-sized enterprises within the park through order linkages, technology diffusion, and standard transmission [20]. Accordingly, the development of industrial parks can no longer be understood simply as an increase in the number of firms or an expansion in industrial scale; rather, it is increasingly manifested in the strengthening of collaboration among internal actors and the stabilization of organizational linkages within the park. On the other hand, as research has continued to deepen, scholars' understanding of collaborative development in industrial parks has gradually expanded from "industrial agglomeration" to "systemic collaboration." Relevant studies have pointed out that relationships among actors within industrial parks extend beyond production division and market transactions to encompass multiple dimensions, including information exchange, technological spillovers, resource sharing, and institutional coordination [21,22]. In particular, in studies on industrial symbiosis, eco-industrial parks, and collaborative innovation, industrial parks are regarded as composite systems jointly composed of firms, administrative bodies, and related supporting actors, whose operational performance depends not only on the efficiency of individual actors but also on whether stable and effective collaborative mechanisms can be established among them [23,24]. From this perspective, the focus of collaborative development in industrial parks has gradually shifted from the

agglomeration effects of firms alone to complementary cooperation, interest linkage, and overall optimization among actors.

2.2. A Study on Multi-Stakeholder Collaborative Governance of Workplace Safety in Industrial Parks

Work safety governance is a critical component in ensuring the safe operation of industrial parks. Given the multiplicity of actors involved in park work safety and the complexity of their roles, scholars have examined this issue from different perspectives and with various methods over different periods. Early studies mainly focused on technical dimensions, including safety-oriented park siting and layout design [25,26], the propagation of accident risks and domino effects [27,28], as well as park risk management and the assessment of work safety capacity [29]. These studies have provided important support for the identification of safety risks and the development of technical prevention and control measures in industrial parks. However, they generally treat governance actors as exogenously given, making it difficult to explain the deeper institutional causes underlying inadequate implementation of work safety responsibilities.

In recent years, although the overall work safety situation in China's industrial parks has improved, the total number of accidents remains high, and major and extraordinarily serious accidents still occur [30,31]. Accident investigation reports released by the emergency management authorities show that such accidents are consistently identified as liability accidents in production safety, and that their occurrence is the joint result of multiple actors failing to fulfill their respective work safety responsibilities [32]. Against this backdrop, scholarly attention has gradually shifted toward the regulatory responsibility system and the construction of governance mechanisms for work safety. For example, Lu et al. [33] argued that a sound governmental work safety regulatory system would motivate firms to take measures to improve their own work safety levels. Ma et al. [34], by developing a sequential game model that jointly considers firms' work safety decisions and governmental safety measures, discussed different types of workplace accidents and different categories of governmental interventions in an effort to minimize the probability of workplace accidents to the greatest extent possible. Hausken et al. [35] introduced an accident-probability model to analyze the interaction among governmental work safety measures and taxation, and firms' safety investment and productivity improvement, with the aim of balancing accident losses against production profits and tax revenues. However, as work safety issues in industrial parks have become increasingly complex, the traditional governance model relying primarily on a single governmental actor has shown clear limitations and has become insufficient to achieve the intended safety governance objectives [36,37]. Constrained by limited regulatory manpower and professional capacity, as well as inadequate safety attitudes among firms [38–41], there is a pressing need to shift from government-centered regulation toward work safety governance mechanisms characterized by the participation of multiple actors [42–44].

2.3. A Study on the Application of Symbiosis Theory in Industrial Collaborative Governance

In studies of industrial collaborative governance, symbiosis theory has been mainly employed to explain the internal logic through which relationships among different actors evolve from competition to cooperation and from fragmentation to coordination. Within industrial systems, enterprises, governments, platform organizations, and other supporting actors gradually develop multiple forms of linkage through long-term interaction, including resource sharing, capability complementarity, interest interdependence, and institutional embeddedness [45,46]. On this basis, symbiosis theory suggests that the overall performance of a system can be sustainably improved only when heterogeneous actors establish relatively stable and mutually beneficial relationships [47,48]. Compared

with traditional analytical perspectives that emphasize the optimal choice of a single actor, symbiosis theory places greater emphasis on the interaction structure among actors, the coordination of interests, and the evolutionary process of cooperation. It has therefore been widely applied to explain issues such as collaboration in industrial clusters, supply chain cooperation, the formation of regional innovation networks, and the optimization of industrial ecosystems [49–52]. Existing studies on the application of symbiosis theory in industrial collaborative governance mainly focus on three aspects. First, symbiosis theory has been used to explain cooperative relationships among upstream and downstream actors in industrial chains, exploring how core enterprises and supporting firms achieve coordinated development through technology diffusion, information sharing, and resource integration [53,54]. Second, it has been applied to analyze the interaction mechanisms among governments, enterprises, and social organizations within regional industrial systems, with particular emphasis on the roles of institutional provision, platform building, and policy guidance in sustaining symbiotic relationships [55,56]. Overall, the value of symbiosis theory in the study of industrial collaborative governance lies primarily in its ability to move beyond the analytical limitations of single-actor and linear-relationship approaches and to capture the continuous interaction and co-evolution of multiple actors from the perspective of the system as a whole.

2.4. Shortcomings of Previous Work and Research Innovations

Although existing studies have examined work safety governance in industrial parks from perspectives such as technical control, government–enterprise cooperation, and multi-actor collaboration, little attention has been paid to the symbiotic relationships among the park management committee, leading enterprises, and park enterprises, nor have scholars systematically revealed, from a continuous dynamic perspective, the linkage mechanisms among actors' behavioral choices, payoff changes, and the park's overall work safety level under different reciprocal symbiosis modes. Static game models mainly focus on one-time strategic decisions, while evolutionary game models generally describe behavioral evolution in discrete stages. Both approaches have limitations in capturing the continuous accumulation and attenuation of work safety outcomes over time. It is worth noting that differential game theory is well suited to describing the continuously evolving strategic interactions among multiple actors in a dynamic system [57,58]. This advantage is particularly important in industrial park work safety governance because the park's work safety level is a continuously changing state variable jointly influenced by the efforts of multiple actors. Moreover, safety equipment, monitoring facilities, emergency response resources, and other forms of safety capital gradually depreciate over time, causing the work safety level to decline in the absence of sustained investment. Differential game theory allows both the accumulation and depreciation of safety capital to be incorporated into a continuous-time analytical framework, thereby providing an appropriate tool for characterizing the dynamic evolution of work safety levels and revealing the cooperation and conflict among multiple stakeholders under different reciprocal symbiosis modes. On this basis, this study adopts the perspective of symbiosis theory and regards work safety governance in industrial parks as a dynamic symbiotic system. Taking the park management committee, leading enterprises, and small and medium-sized enterprises within the park as the research objects, it constructs a differential game model in which the work safety level evolves over time, and investigates the changing patterns of the work safety effort levels, discounted payoffs of symbiotic units, and the overall work safety level of the park under different decision-making approaches and reciprocal symbiosis modes. The aim is to provide a theoretical basis and decision-making reference for improving the

effectiveness of work safety governance and promoting the development of sustainable industrial parks.

3. Model Construction

3.1. Problem Description

The principal stakeholders in the development of industrial parks include the park management committee, leading enterprises, and park enterprises. As the core actor in park governance and service provision, the park management committee undertakes functions such as policy formulation, resource allocation, supervision and management, and the provision of public services, with the aim of creating a well-regulated and orderly development environment for park enterprises. As the driving force behind industrial development within the park, leading enterprises, by virtue of their strong technological, financial, and market advantages, attract a large number of industrially related park enterprises to agglomerate and gradually form close relationships of division of labor, cooperation, and supporting interdependence [11,24,46]. As important components of the industrial chain, park enterprises participate in product development, production collaboration, and market expansion under the leadership of leading enterprises, thereby jointly sustaining the stable operation of the park's industrial system. Within such a highly interconnected industrial organizational structure, once a work safety accident occurs in a park enterprise, it may not only trigger a domino-like chain reaction through production collaboration, supply chain transmission, and spatial proximity effects [10,27,28,35], but also lead to industrial chain disruptions, resource waste, and the spillover of external risks, thereby affecting the overall operational efficiency of the park and the stability of the regional economy. It is therefore evident that improving the level of work safety is not only related to accident prevention and control capacity, but also directly affects industrial chain stability, system resilience, and the development of sustainable industrial parks.

Improving the level of work safety in industrial parks is a long-term process that requires sustained investment and the coordinated efforts of multiple actors [3,34,41]. In seeking to enhance work safety performance, the park management committee, leading enterprises, and park enterprises often need to make dynamic trade-offs between safety-related investment and economic returns. At present, however, work safety governance in industrial parks still exhibits pronounced features of fragmented responsibility and insufficient coordination. The governance responsibilities of the park management committee, the leading role of core enterprises, and the primary responsibilities of park enterprises have not yet been effectively integrated. In practice, the park management committee tends to place greater emphasis on access approval, inspection and enforcement, and post-accident accountability, while giving insufficient attention to process-oriented supervision, collaborative incentives, and the provision of institutionalized policy tools. Although leading enterprises possess significant advantages in work safety technologies, equipment allocation, and managerial experience, their functions in resource sharing, technical assistance, and collaborative safety empowerment have not been fully realized, due in part to unclear benefit-sharing mechanisms and inadequate incentives. Meanwhile, constrained by limitations in capital, technology, and human resources, park enterprises generally lack the capacity to achieve sustained improvements in work safety. Their safety-related investment often displays strong passivity and a short-term compliance orientation, typically characterized by intensive rectification efforts before inspections followed by a return to routine practices afterward.

It should be emphasized that, under the combined effects of spatial agglomeration and industrial interdependence, park enterprises are connected not only through business linkages and factor flows, but also through the imitation of safety-related behaviors, the

diffusion of experience, and the transmission of risks [36,43]. In practice, leading enterprises often occupy a dominant position within the industrial chain and exert a driving effect on park enterprises through order coordination, technical assistance, safety standard transmission, performance assessment, and demonstration effects. Under such a driving effect, leading enterprises can promote the diffusion of advanced safety management experience and facilitate the sharing of work safety resources among park enterprises. Therefore, the resource-sharing coefficient is introduced to characterize the intensity of work safety resource sharing from leading enterprises to park enterprises under the leading-enterprise driving effect. In the absence of effective mechanisms for resource sharing, cost sharing, and collaborative incentives, the work safety management advantages of leading enterprises are difficult to translate into governance effectiveness at the park level, while the park management committee is likewise unable to effectively integrate the technological supply of leading enterprises with the actual needs of park enterprises. As a result, work safety governance in industrial parks may fall into a vicious cycle of “insufficient investment–coordination failure–risk accumulation.” This not only hampers improvements in the overall work safety level of the park, but also weakens its capacity for stable operation and its potential for sustainable development. Therefore, it is imperative to establish a reciprocal symbiosis-based collaborative governance model that simultaneously accommodates economic returns, work safety performance, and the sustainable operational capacity of industrial parks. By optimizing the mechanisms of resource sharing, cost sharing, and interest coordination among multiple actors, such a model can promote a shift in industrial park work safety governance from fragmented responses to systemic collaboration.

3.2. Model Notation and Assumptions

This study focuses on an industrial park symbiotic system composed of the park management committee, leading enterprises, and park enterprises. Taking into account the dynamic evolution of the industrial park’s work safety level over time, it investigates the reciprocal symbiosis mechanism through which the work safety level of the industrial park can be improved while simultaneously increasing the benefits of the park management committee, leading enterprises, and park enterprises, by analyzing the work safety effort levels and payoffs of these three actors. The model notations are presented in Table 1.

Table 1. Symbols and Definitions of Model Parameters.

Symbol	Definition	References
R	Total payoff of the industrial park	[59]
$\varepsilon_1, \varepsilon_2$	Payoff allocation coefficients for the leading enterprise and park enterprises	[60]
S_G, S_L, S_E	Work safety effort levels of the park management committee, leading enterprise, and park enterprises	[61]
μ_G, μ_L, μ_E	Effort cost coefficients of the park management committee, leading enterprise, and park enterprises in work safety	[62]
$S(t)$	Work safety level of the industrial park at time t	[63]
α, β, γ	Impact coefficients of the work safety efforts of the park management committee, leading enterprise, and park enterprises	[63]
ω	Work safety resource-sharing coefficient from the leading enterprise to park enterprises under the driving effect	[64]
σ	Cost coefficient of work safety resource sharing from the leading enterprise to park enterprises	[64]

Table 1. Cont.

Symbol	Definition	References
θ_L	Cost-sharing coefficient of the park management committee for the leading enterprise	[65]
P	Probability of a work safety accident	[66]
τ	Impact coefficient of the industrial park's work safety level on the probability of a work safety accident	[66]
D_G, D_L, D_E	Losses of the park management committee, leading enterprise, and park enterprises in the event of a work safety accident	[66]
ξ	Decay rate of the work safety level	[67]
ρ	Discount rate	[68]

For modeling purposes, the following assumptions are made in this study:

- (1) From the perspective of symbiosis theory, an industrial park consists of three symbiotic actors: the park management committee, leading enterprises, and park enterprises. In this study, the efforts made by the park management committee, leading enterprises, and park enterprises with respect to work safety in the industrial park are collectively referred to as work safety efforts. The total payoff of the industrial park is distributed in three parts: one part is allocated to park enterprises in the form of supporting-service returns, one part is allocated to leading enterprises in the form of industrial investment returns, and the remaining part is obtained by the park management committee. It is assumed that the total payoff of the industrial park is R , of which the leading enterprise obtains ε_1 , the park enterprises obtain ε_2 , and the park management committee obtains $1 - \varepsilon_1 - \varepsilon_2$. The allocation coefficients are determined by the respective contributions and bargaining power of the three actors.
- (2) The work safety effort levels of the park management committee, the leading enterprise, and the park enterprises are denoted by S_G , S_L , and S_E , respectively. Considering that the costs incurred by each actor in work safety are related to its effort level, and in accordance with the convexity property of the cost function [61,62], the work safety effort costs of the park management committee, the leading enterprise, and the park enterprises are denoted by $\frac{1}{2}\mu_G S_G^2$, $\frac{1}{2}\mu_L S_L^2$, and $\frac{1}{2}\mu_E S_E^2$, respectively.
- (3) The work safety level of the industrial park is a continuously evolving state variable. Its evolution depends not only on the work safety efforts of the park management committee, leading enterprises, and park enterprises, but also on the natural depreciation of safety-related assets, including safety equipment, monitoring facilities, emergency response resources, and accumulated safety management knowledge. Therefore, in the absence of continuous safety investment, the work safety level will gradually decline over time. The dynamic evolution of the work safety level of the industrial park over time can therefore be expressed by the following differential equation:

$$\begin{cases} S'(t) = \alpha S_G(t) + \beta S_L(t) + \gamma S_E(t) - \xi S(t) \\ S(0) = S_0 \geq 0 \end{cases} \quad (1)$$

where ξ denotes the safety capital depreciation coefficient, S_0 denotes the initial work safety level of the industrial park, $S'(t)$ denotes the instantaneous rate of change in the work safety level, and $S(t)$ denotes the work safety level of the industrial park at time t .

- (4) Existing studies have found a significant inverse relationship between improvements in work safety levels and the incidence of work safety accidents [66]. Therefore, the probability of a work safety accident in the industrial park is denoted by $P - \tau S(t)$.

3.3. Construction of the Benchmark Model

First, a benchmark model without leading-enterprise dominance or park-management-committee guidance is established. Based on the above assumptions of the model, the objective payoff functions of the park management committee, the leading enterprise, and the park enterprises can be obtained as follows:

$$\pi_G = \int_0^\infty e^{-\rho t} [(1 - \varepsilon_1 - \varepsilon_2)R - \frac{\mu_G S_G^2}{2} - (P - \tau S)D_G] dt \quad (2)$$

$$\pi_L = \int_0^\infty e^{-\rho t} [\varepsilon_1 R - \frac{\mu_L S_L^2}{2} - (P - \tau S)D_L] dt \quad (3)$$

$$\pi_E = \int_0^\infty e^{-\rho t} [\varepsilon_2 R - \frac{\mu_E S_E^2}{2} - (P - \tau S)D_E] dt \quad (4)$$

The decision problem faced by the park management committee, the leading enterprise, and the park enterprises in improving the work safety level of the industrial park is, subject to the constraint $\begin{cases} S'(t) = \alpha S_G + \beta S_L + \gamma S_E - \zeta S(t) \\ S(0) = S_0 \geq 0 \end{cases}$, to choose π_G , π_L , and π_E so as to maximize S_G , S_L , and S_E , respectively.

4. Model Solutions Under Different Decision-Making Scenarios

Across different stages of work safety governance in industrial parks, the degree of coordination among the park management committee, leading enterprises, and park enterprises in work safety investment decisions varies significantly. In practice, during the routine operation of most industrial parks, the park management committee, leading enterprises, and park enterprises still make decisions on work safety investment and effort levels primarily according to the principle of maximizing their own respective payoffs. In the absence of effective coordination mechanisms, each actor makes decisions independently based on its own objectives, thereby giving rise to a typical decentralized decision-making scenario. Meanwhile, with the continuous improvement of park governance systems, some industrial parks have gradually strengthened coordination among internal actors by establishing joint work safety management mechanisms, cost-sharing arrangements for work safety investment, and benefit-sharing mechanisms. Under such conditions, the park management committee, leading enterprises, and park enterprises no longer make decisions entirely independently in work safety governance; instead, they increasingly aim at improving the overall safety performance and long-term development interests of the park, thereby exhibiting centralized or coordinated decision-making characteristics. In this process, work safety governance in industrial parks evolves from “loose cooperation” toward “deep collaboration.” Based on the above analysis, this study constructs work safety governance models for industrial parks under both decentralized and centralized decision-making scenarios, so as to examine the effects of different decision-making mechanisms on the park’s work safety level and overall payoff.

4.1. Decentralized Decision-Making

Under the decentralized decision-making scenario, the park management committee, leading enterprises, and park enterprises determine their respective optimal work safety effort levels according to the principle of payoff maximization. By constructing the

Hamilton–Jacobi–Bellman (HJB) equations, the optimal strategies of the park management committee, leading enterprises, and park enterprises can be derived.

Accordingly, under decentralized decision-making, the optimal strategies of the park management committee, leading enterprises, and park enterprises are obtained as follows (denoted by the superscript A):

$$S_G^A = \frac{\alpha \tau D_G}{\mu_G(\xi + \rho)} \quad (5)$$

$$S_L^A = \frac{\beta \tau D_L}{\mu_L(\xi + \rho)} \quad (6)$$

$$S_E^A = \frac{\gamma \tau D_E}{\mu_E(\xi + \rho)} \quad (7)$$

Proof. Under the decentralized decision-making scenario, the model is solved by backward induction. According to the optimal control approach, there exist continuously differentiable value functions $V_G(S)$, $V_L(S)$, and $V_E(S)$ that satisfy the HJB equations. $\square$

$$\rho V_G(S) = \max_{S_G} \left\{ [R(1 - \varepsilon_1 - \varepsilon_2) - \frac{\mu_G S_G^2}{2} - (P - \tau S)D_G + V_G'(S)(\alpha S_G + \beta S_L + \gamma S_E - \xi S)] \right\} \quad (8)$$

$$\rho V_L(S) = \max \left\{ [R\varepsilon_1 - \frac{\mu_L S_L^2}{2} - (P - \tau S)D_L] + V_L'(S)(\alpha S_G + \beta S_L + \gamma S_E - \xi S) \right\} \quad (9)$$

$$\rho V_E(S) = \max \left\{ [R\varepsilon_2 - \frac{\mu_E S_E^2}{2} - (P - \tau S)D_E + V_E'(S)(\alpha S_G + \beta S_L + \gamma S_E - \xi S)] \right\} \quad (10)$$

Based on the condition of the first-order derivative of the maximization function, we obtain:

$$(S_G, S_L, S_E) = \left(\frac{\alpha V_G'(S)}{\mu_G}, \frac{\beta V_L'(S)}{\mu_L}, \frac{\gamma V_E'(S)}{\mu_E} \right) \quad (11)$$

Substituting Equation (11) into the HJB equation and simplifying yields:

$$\rho V_G(S) = (\tau D_G - \xi V_G')S + R(1 - \varepsilon_1 - \varepsilon_2) + \frac{\gamma^2 V_E' V_L'}{\mu_E} + \frac{(\alpha V_G')^2}{2\mu_G} + \frac{\beta^2 V_G' V_L'}{\mu_L} - PD_G \quad (12)$$

$$\rho V_L(S) = (\tau D_L - \xi V_L')S + R\varepsilon_1 + \frac{\gamma^2 V_E' V_L'}{\mu_E} + \frac{\alpha^2 V_G' V_L'}{\mu_G} + \frac{(\beta V_L')^2}{2\mu_L} - PD_L \quad (13)$$

$$\rho V_E(S) = (\tau D_E - \xi V_E')S + R\varepsilon_2 + \frac{(\gamma V_E')^2}{2\mu_E} + \frac{\alpha^2 V_G' V_E'}{\mu_G} + \frac{\beta^2 V_E' V_L'}{\mu_L} - PD_E \quad (14)$$

It can be seen from Equations (12)–(14) that the linear optimal value function with respect to S is a solution to the HJB equation. Therefore, let

$$\begin{cases} V_G(S) = t_1 S + t_2 \\ V_L(S) = m_1 S + m_2 \\ V_E(S) = n_1 S + n_2 \end{cases} \quad (15)$$

Here, t_1 , t_2 , m_1 , m_2 , n_1 and n_2 are undetermined constants. Substituting Equation (15) into the HJB equation above yields:

$$t_1 = \frac{\tau D_G}{\xi + \rho} \quad (16)$$

$$m_1 = \frac{\tau D_L}{\xi + \rho} \quad (17)$$

$$n_1 = \frac{\tau D_E}{\xi + \rho} \quad (18)$$

$$t_2 = \frac{1}{\rho} [R(1 - \varepsilon_1 - \varepsilon_2) - D_G P + \frac{r^2 \tau^2 D_E D_G}{\mu_E (\xi + \rho)^2} + \frac{\alpha^2 \tau^2 D_G^2}{2(\xi + \rho)^2 \mu_G} + \frac{D_L D_G \beta^2 \tau^2}{\mu_L (\xi + \rho)^2}] \quad (19)$$

$$m_2 = \frac{1}{\rho} [R\varepsilon_1 - P D_L + \frac{r^2 \tau^2 D_E D_L}{\mu_E (\xi + \rho)^2} + \frac{\alpha^2 \tau^2 D_L D_G}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2 \tau^2 D_L^2}{2\mu_L (\xi + \rho)^2}] \quad (20)$$

$$n_2 = \frac{1}{\rho} [R\varepsilon_2 - P D_E + \frac{r^2 \tau^2 D_E^2}{2\mu_E (\xi + \rho)^2} + \frac{\alpha^2 \tau^2 D_E D_G}{(\xi + \rho)^2 \mu_G} + \frac{D_L D_E \beta^2 \tau^2}{\mu_L (\xi + \rho)^2}] \quad (21)$$

Substituting Equations (16)–(18) into Equation (11) yields the optimal strategies for the park management committee, the leading enterprise, and the park enterprises as follows:

$$(S_G^A, S_L^A, S_E^A) = (\frac{\alpha \tau D_G}{\mu_G (\xi + \rho)}, \frac{\beta \tau D_L}{\mu_L (\xi + \rho)}, \frac{\gamma \tau D_E}{\mu_E (\xi + \rho)}) \quad (22)$$

The optimal strategies for the park management committee, leading enterprises, and park enterprises have been established. Under these conditions, the present values of the optimal returns for each entity are as follows:

$$V_G^A = \frac{\tau D_G}{\xi + \rho} S_0 + \frac{1}{\rho} [R(1 - \varepsilon_1 - \varepsilon_2) - D_G P + \frac{r^2 \tau^2 D_E D_G}{\mu_E (\xi + \rho)^2} + \frac{\alpha^2 \tau^2 D_G^2}{2(\xi + \rho)^2 \mu_G} + \frac{D_L D_G \beta^2 \tau^2}{\mu_L (\xi + \rho)^2}] \quad (23)$$

$$V_L^A = \frac{\tau D_L}{\xi + \rho} S_0 + \frac{1}{\rho} [R\varepsilon_1 - P D_L + \frac{r^2 \tau^2 D_E D_L}{\mu_E (\xi + \rho)^2} + \frac{\alpha^2 \tau^2 D_L D_G}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2 \tau^2 D_L^2}{2\mu_L (\xi + \rho)^2}] \quad (24)$$

$$V_E^A = \frac{\tau D_E}{\xi + \rho} S_0 + \frac{1}{\rho} [R\varepsilon_2 - P D_E + \frac{r^2 \tau^2 D_E^2}{2\mu_E (\xi + \rho)^2} + \frac{\alpha^2 \tau^2 D_E D_G}{(\xi + \rho)^2 \mu_G} + \frac{D_L D_E \beta^2 \tau^2}{\mu_L (\xi + \rho)^2}] \quad (25)$$

4.2. Centralized Decision-Making

Under the centralized decision-making scenario, the park management committee, leading enterprises, and park enterprises act as an integrated whole and jointly determine the optimal work safety investment decisions with the objective of maximizing the overall benefits of the industrial park. In this case, the objective function of the industrial park is given by:

$$\pi = \pi_G + \pi_L + \pi_E = \int_0^\infty e^{-\rho t} \{R - \frac{\mu_L S_L^2}{2} - (P - \tau S) D_L - \frac{\mu_E S_E^2}{2} - (P - \tau S) D_E - \frac{\mu_G S_G^2}{2} - (P - \tau S) D_G\} dt \quad (26)$$

Accordingly, under centralized decision-making, the optimal strategies of the park management committee, the leading enterprise, and the park enterprises are obtained as follows (denoted by the superscript B):

$$S_G^B = \frac{\alpha \tau (D_G + D_L + D_E)}{\mu_G (\xi + \rho)} \quad (27)$$

$$S_L^B = \frac{\beta \tau (D_G + D_L + D_E)}{\mu_L (\xi + \rho)} \quad (28)$$

$$S_E^B = \frac{\gamma \tau (D_G + D_L + D_E)}{\mu_E (\xi + \rho)} \quad (29)$$

Proof. Under the centralized decision-making scenario, the model is solved by backward induction. According to the optimal control approach, there exists a continuously differentiable value function that satisfies the HJB equation. $\square$

$$\rho V(S) = \max_{S_G, S_L, S_E} \left\{ R - \frac{\mu_G S_G^2}{2} - \frac{\mu_L S_L^2}{2} - \frac{\mu_E S_E^2}{2} - (P - \tau S)(D_G + D_L + D_E) \right\} + V'(S)(\alpha S_G + \beta S_L + \gamma S_E - \xi S(t)) \quad (30)$$

According to the first-order conditions for maximization, we obtain:

$$(S_G, S_L, S_E) = \left(\frac{\alpha V'(S)}{\mu_G}, \frac{\beta V'(S)}{\mu_L}, \frac{\gamma V'(S)}{\mu_E} \right) \quad (31)$$

Substituting Equation (31) into the HJB equation and rearranging yields:

$$\rho V(S) = R + \frac{(\alpha V'(S))^2}{2\mu_G} + \frac{(\beta V'(S))^2}{2\mu_L} + \frac{(\gamma V'(S))^2}{2\mu_E} - P(D_G + D_L + D_E) + [\tau(D_G + D_L + D_E) - \xi V'(S)]S \quad (32)$$

As can be seen from Equation (32), the linear optimal value function with respect to S is a solution to the HJB equation. Therefore, let

$$V(S) = f_1 S + f_2 \quad (33)$$

where f_1 and f_2 are constants to be determined. Substituting Equation (33) into the above HJB equation yields:

$$f_1 = \frac{\tau(D_G + D_L + D_E)}{\xi + \rho} \quad (34)$$

$$f_2 = \frac{1}{\rho} \left\{ R + \frac{\alpha^2 \tau^2 (D_G + D_E + D_L)^2}{2\mu_G (\xi + \rho)^2} + \frac{\beta^2 \tau^2 (D_G + D_E + D_L)^2}{2\mu_L (\xi + \rho)^2} + \frac{\gamma^2 \tau^2 (D_G + D_E + D_L)^2}{2\mu_E (\xi + \rho)^2} - P(D_G + D_L + D_E) \right\} \quad (35)$$

Substituting Equation (34) into Equation (31), the optimal strategies of the park management committee, the leading enterprise, and the park enterprises can be obtained as follows:

$$(S_G^B, S_L^B, S_E^B) = \left(\frac{\alpha \tau (D_L + D_E + D_G)}{\mu_G (\xi + \rho)}, \frac{\beta \tau (D_G + D_L + D_E)}{\mu_L (\xi + \rho)}, \frac{\gamma \tau (D_G + D_L + D_E)}{\mu_E (\xi + \rho)} \right) \quad (36)$$

The optimal strategies of the park management committee, the leading enterprise, and the park enterprises are thus proved. Under this condition, the optimal discounted payoff of the industrial park is given by:

$$V^B = \frac{\tau(D_G + D_L + D_E)}{\xi + \rho} S_0 + \frac{1}{\rho} \left[R + \frac{\alpha^2 \tau^2 (D_G + D_E + D_L)^2}{2\mu_G (\xi + \rho)^2} + \frac{\beta^2 \tau^2 (D_G + D_E + D_L)^2}{2\mu_L (\xi + \rho)^2} + \frac{\gamma^2 \tau^2 (D_G + D_E + D_L)^2}{2\mu_E (\xi + \rho)^2} - P(D_G + D_L + D_E) \right] \quad (37)$$

4.3. Comparison Between Decentralized Decision-Making and Centralized Decision-Making

By comparing the solutions of the model under the decentralized and centralized decision-making scenarios, the following proposition can be obtained.

Proposition 1. Under the centralized decision-making scenario, the work safety effort levels of the park management committee, the leading enterprise, and the park enterprises—denoted by S_G^B , S_L^B , and S_E^B , respectively—are all higher than S_G^A , S_L^A , and S_E^A under the decentralized decision-making scenario. Likewise, the work safety level and the overall discounted payoff of

the industrial park under centralized decision-making, denoted by S^B and V^B , are both higher than S^A and V^A under the decentralized decision-making scenario.

Proof. According to Equations (5)–(7) and (27)–(29), we obtain $S_G^B - S_G^A = \frac{\alpha\tau(D_E+D_L)}{(\xi+\rho)\mu_G} > 0$, $S_L^B - S_L^A = \frac{\beta\tau(D_E+D_G)}{(\xi+\rho)\mu_L} > 0$, $S_E^B - S_E^A = \frac{\gamma\tau(D_E+D_G)}{(\xi+\rho)\mu_E} > 0$, and $S_G^B - S_G^A = \frac{\alpha\tau(D_E+D_L)}{(\xi+\rho)\mu_G} > 0$. For ease of comparative analysis, expression (1) is simplified by letting $M = \alpha S_G + \beta S_L + \gamma S_E$; then $S'(t) = M - \xi S(t)$, from which $S = \frac{M}{\xi} + (S_0 - \frac{M}{\xi})e^{-\xi t}$ is obtained, and further $\frac{dS}{dM} = \frac{1}{\xi}(1 - e^{-\xi t}) > 0$. Therefore, S is an increasing function of M , which implies that $S^B > S^A$. Under the decentralized decision-making scenario, the overall discounted payoff is $V^A = V_G^A + V_L^A + V_E^A$; hence,
$$V^A = \frac{\tau(D_G+D_L+D_E)}{\xi+\rho}S_0 + \frac{1}{\rho}\left[R + \frac{\alpha^2\tau^2(D_G^2+2D_LD_G+2D_GD_E)}{2\mu_G(\xi+\rho)^2} + \frac{\beta^2\tau^2(D_L^2+2D_LD_E+2D_GD_L)}{2\mu_L(\xi+\rho)^2} + \frac{\gamma^2\tau^2(D_E^2+2D_LD_E+2D_GD_E)}{2\mu_E(\xi+\rho)^2} - P(D_G + D_L + D_E)\right], V^B - V^A = \frac{1}{\rho}\left[\frac{\alpha^2\tau^2(D_E+D_L)^2}{2\mu_G(\xi+\rho)^2} + \frac{\beta^2\tau^2(D_G+D_L)^2}{2\mu_L(\xi+\rho)^2} + \frac{\gamma^2\tau^2(D_G+D_L)^2}{2\mu_E(\xi+\rho)^2}\right] > 0. \quad \square$$
 Thus, the proof is completed.

Proposition 1 shows that, compared with the decentralized decision-making mode, when the park management committee, leading enterprises, and park enterprises make decisions as an integrated whole, both the work safety level and the overall discounted payoff of the park symbiotic system are higher. In practice, however, these actors tend to pursue the maximization of their own interests and therefore find it difficult to make work safety decisions as a fully integrated entity. It is therefore particularly necessary to design reciprocal symbiosis modes that can effectively balance economic benefits while significantly improving the work safety level of industrial parks.

5. Design of Reciprocal Symbiosis Modes

From the perspective of symbiosis theory, reciprocal symbiosis in industrial park work safety governance is a process accompanied by the continuous deepening of coordination among participating actors, evolving from a low level of collaboration to a high level of collaboration. Based on differences in the ways the park management committee, leading enterprises, and park enterprises coordinate in work safety governance, this study constructs three reciprocal symbiosis modes, corresponding, respectively, to the low-collaboration stage, the collaboration-enhancement stage, and the deep-collaboration stage. These three modes progress step by step in terms of the leading governance actor, the form of resource sharing, and the degree of goal integration, and together characterize the evolutionary path of industrial park work safety governance from fragmented cooperation to unified coordination.

5.1. Leading-Enterprise-Dominated Mode

The leading-enterprise-dominated mode refers to a governance mode in which the leading enterprise acts as the key driver for improving the work safety level of the industrial park. Relying on its advantageous market position, accumulated work safety technologies, and managerial experience, the leading enterprise identifies the needs of park enterprises through a resource-sharing mechanism and makes its high-quality work safety resources—such as technologies, equipment, and managerial know-how—available for use or reference by park enterprises, thereby proactively providing low-cost and high-efficiency support for their work safety improvement (thus, it is assumed that the cost coefficient of resource sharing satisfies $(\sigma < \frac{1}{2})$). Since the effectiveness of resource sharing depends on the extent to which park enterprises actively engage in work safety improvement, the

utilization and absorption of shared resources are assumed to increase with the work safety effort level of park enterprises. A higher level of safety effort requires more extensive technical assistance, training, equipment support, information exchange, and coordination from the leading enterprise. Therefore, the effective volume of shared resources is represented by ωS_E , and the leading enterprise incurs a unit sharing cost σ , resulting in a total sharing cost of $\sigma\omega S_E$. Under this mode, however, the degree of collaboration among the three actors involved in improving the park's work safety level remains relatively limited. Accordingly, the objective payoff functions of the park management committee, the leading enterprise, and the park enterprises are given as follows:

$$\pi_G = \int_0^\infty e^{-\rho t} [(1 - \varepsilon_1 - \varepsilon_2)R - \frac{\mu_G S_G^2}{2} - (P - \tau S)D_G] dt \quad (38)$$

$$\pi_L = \int_0^\infty e^{-\rho t} [\varepsilon_1 R - \frac{\mu_L S_L^2}{2} - (P - \tau S)D_L - \sigma\omega S_E] dt \quad (39)$$

$$\pi_E = \int_0^\infty e^{-\rho t} [\varepsilon_2 R - \frac{\mu_E S_E^2}{2} - (P - \tau S)D_E + \omega S_E] dt \quad (40)$$

Accordingly, under decentralized decision-making, the optimal strategies of the park management committee, the leading enterprise, and the park enterprises are obtained as follows (denoted by the superscript H):

$$S_G^H = \frac{\alpha\tau D_G}{\mu_G(\xi + \rho)} \quad (41)$$

$$S_L^H = \frac{\beta\tau D_L}{\mu_L(\xi + \rho)} \quad (42)$$

$$S_E^H = \frac{\omega(\xi + \rho) + \gamma\tau D_E}{\mu_E(\xi + \rho)} \quad (43)$$

Proof. The derivation follows steps similar to those under the decentralized decision-making scenario and is therefore omitted for brevity. $\square$

Under this mode, the optimal payoffs of the park management committee, the leading enterprise, and the park enterprises are, respectively, given by:

$$V_G^H = \frac{\tau D_G}{\xi + \rho} S_0 + \frac{1}{\rho} [R(1 - \varepsilon_1 - \varepsilon_2) - D_G P + \frac{r\tau(\omega + \frac{\gamma\tau D_E}{\xi + \rho})D_G}{\mu_E(\xi + \rho)} + \frac{\alpha^2\tau^2 D_G^2}{2(\xi + \rho)^2 \mu_G} + \frac{D_L D_G \beta^2 \tau^2}{\mu_L(\xi + \rho)^2}] \quad (44)$$

$$V_L^H = \frac{\tau D_L}{\xi + \rho} S_0 + \frac{1}{\rho} \left[R\varepsilon_1 - P D_L - \frac{\omega\sigma(\omega + \frac{\gamma\tau D_E}{\xi + \rho})}{\mu_E} + \frac{\gamma\tau(\omega + \frac{\gamma\tau D_E}{\xi + \rho})D_L}{(\xi + \rho)\mu_E} + \frac{\alpha^2\tau^2 D_G D_L}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2\tau^2 D_L^2}{2(\xi + \rho)^2 \mu_L} \right] \quad (45)$$

$$V_E^H = \frac{\tau D_E}{\xi + \rho} S_0 + \frac{1}{\rho} \left[R\varepsilon_2 - P D_E + \frac{\omega(\omega + \frac{\gamma\tau D_E}{\xi + \rho})}{\mu_E} + \frac{\gamma\tau D_E(\omega + \frac{\gamma\tau D_E}{\xi + \rho})}{(\xi + \rho)\mu_E} - \frac{(\omega + \frac{\gamma\tau D_E}{\xi + \rho})^2}{2\mu_E} + \frac{\alpha^2\tau^2 D_E D_G}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2\tau^2 D_E D_L}{(\xi + \rho)^2 \mu_L} \right] \quad (46)$$

Proposition 2. Compared with the decentralized decision-making scenario without leading-enterprise dominance or park-management-committee guidance, the leading-enterprise-dominated mode does not affect the work safety effort levels of the park management committee or the leading enterprise, but it increases the work safety effort level of park enterprises. Moreover, the larger the leading enterprise's work safety resource-sharing coefficient ω to park enterprises, the higher the

work safety effort level S_E^H of park enterprises. Under the leading-enterprise-dominated mode, the park's work safety level S^H is higher than S^A under the decentralized decision-making mode without leading-enterprise dominance or park-management-committee guidance. The overall discounted payoff of the industrial park under the leading-enterprise-dominated mode, V^H , is also higher than the overall discounted payoff V^A under the decentralized decision-making mode. For the discounted payoffs of the park management committee and park enterprises, V_L^H and V_E^H under the leading-enterprise-dominated mode are higher than V_L^A and V_E^A under the decentralized decision-making mode. When $\omega < \frac{\gamma\tau(D_L - \sigma D_E)}{(\xi + \rho)\sigma}$, the discounted payoff of the leading enterprise under the leading-enterprise-dominated mode, V_G^H is higher than V_G^A under the decentralized decision-making mode.

Proof. According to Equations (5)–(7) and (41)–(43), we obtain $S_G^H - S_G^A = 0$, $S_L^H - S_L^A = 0$, $S_E^H - S_E^A = \frac{\omega}{\mu_E} > 0$; since $S_G^H + S_L^H + S_E^H - (S_G^A + S_L^A + S_E^A) = \frac{\omega}{\mu_E} > 0$, so $S^H > S^A$; $V^H - V^A = \frac{(1-\sigma)\omega\gamma\tau D_E + \omega\gamma\tau}{\mu_E(\xi + \rho)} + \frac{(1-2\sigma)\omega^2}{2\mu_E} > 0$; $V_G^H - V_G^A = \frac{\gamma\tau\omega}{\mu_E(\xi + \rho)} > 0$; $V_L^H - V_L^A = \frac{\gamma\tau\omega D_L - \sigma\omega[\omega(\xi + \rho) + \gamma\tau D_E]}{\mu_E(\xi + \rho)}$, when $\omega < \frac{\gamma\tau(D_L - \sigma D_E)}{(\xi + \rho)\sigma}$, $V_L^H - V_L^A > 0$; $V_E^H - V_E^A = \frac{\omega^2}{2\mu_E} + \frac{\gamma\tau\omega D_E}{2\mu_E(\xi + \rho)} > 0$.

Thus, the proof is completed. $\square$

5.2. Park Management Committee-Led Model

The park-management-committee-led mode refers to a governance mode in which the park management committee acts as the initiator and leading force in improving the work safety level of the industrial park. It promotes work safety governance in the park through innovative incentive mechanisms, specifically by accurately identifying the needs of leading enterprises and park enterprises and using policy instruments such as subsidies and tax incentives to share the additional costs incurred by leading enterprises in supporting the work safety improvement of park enterprises, including expenditures on technical assistance, joint training, and equipment sharing. In this way, leading enterprises are encouraged to continuously strengthen their own work safety management through technological upgrading, equipment renewal, and managerial optimization, and to disseminate these achievements as demonstrative practices to other enterprises in the park, thereby helping park enterprises improve their work safety standards at lower cost and with higher efficiency and proactively advancing the overall work safety level of the industrial park. Under this mode, the degree of collaboration among the three actors involved in improving the park's work safety level is relatively high. Accordingly, the objective payoff functions of the park management committee, the leading enterprise, and the park enterprises are given as follows:

$$\pi_G = \int_0^\infty e^{-\rho t} [R(1 - \varepsilon_1 - \varepsilon_2) - \theta_L \frac{\mu_L S_L^2}{2} - \frac{\mu_G S_G^2}{2} - (P - \tau S) D_G] dt \quad (47)$$

$$\pi_L = \int_0^\infty e^{-\rho t} [R\varepsilon_1 - (1 - \theta_L) \frac{\mu_L S_L^2}{2} - (P - \tau S) D_L] dt \quad (48)$$

$$\pi_E = \int_0^\infty e^{-\rho t} [R\varepsilon_2 - \frac{\mu_E S_E^2}{2} - (P - \tau S) D_E] dt \quad (49)$$

Under decentralized decision-making, the optimal strategies for the Park Management Committee, the leading enterprise, and the enterprises in the park are, in order (denoted by superscript J):

$$S_G^J = \frac{\alpha\tau D_G}{\mu_G(\xi + \rho)} \quad (50)$$

$$S_L^J = \frac{\beta\tau D_L}{\mu_L(\xi + \rho)(1 - \theta_L)} \quad (51)$$

$$S_E^J = \frac{\gamma\tau D_E}{\mu_E(\xi + \rho)} \quad (52)$$

Proof. The derivation follows steps similar to those under the decentralized decision-making scenario and is therefore omitted for brevity. $\square$

Under this mode, the optimal payoffs of the park management committee, the leading enterprise, and the park enterprises are respectively given by:

$$V_G^J = \frac{\tau D_G}{\xi + \rho} S_0 + \frac{1}{\rho} \left[-PD_G + R(1 - \varepsilon_1 - \varepsilon_2) + \frac{\gamma^2 \tau^2 D_E D_G}{(\xi + \rho)^2 \mu_E} + \frac{\alpha^2 \tau^2 D_G^2}{2(\xi + \rho)^2 \mu_G} + \frac{\beta^2 \tau^2 D_G D_L}{(\xi + \rho)^2 (1 - \theta_L) \mu_L} - \frac{\beta^2 \tau^2 D_L^2 \theta_L}{2(\xi + \rho)^2 (1 - \theta_L)^2 \mu_L} \right] \quad (53)$$

$$V_L^J = \frac{\tau D_L}{\xi + \rho} S_0 + \frac{1}{\rho} \left[-PD_L + R\varepsilon_1 + \frac{\gamma^2 \tau^2 D_E D_L}{(\xi + \rho)^2 \mu_E} + \frac{\alpha^2 \tau^2 D_G D_L}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2 \tau^2 D_L^2}{2(\xi + \rho)^2 (1 - \theta_L) \mu_L} \right] \quad (54)$$

$$V_E^J = \frac{\tau D_E}{\xi + \rho} S_0 + \frac{1}{\rho} \left[-PD_E + R\varepsilon_2 + \frac{\gamma^2 \tau^2 D_E^2}{2(\xi + \rho)^2 \mu_E} + \frac{\alpha^2 \tau^2 D_E D_G}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2 \tau^2 D_E D_L}{(\xi + \rho)^2 (1 - \theta_L) \mu_L} \right] \quad (55)$$

Proposition 3. Compared with the decentralized decision-making scenario without leading-enterprise dominance or park-management-committee guidance, the park-management-committee-led mode does not affect the work safety effort levels of the park management committee or park enterprises, but it increases the work safety effort level of the leading enterprise. Moreover, the larger the cost-sharing coefficient θ_L of the park management committee for the leading enterprise, the higher the work safety effort level S_L^J of the leading enterprise. Under the park-management-committee-led mode, the work safety level of the industrial park, S^J , is higher than the work safety level S^A under the decentralized decision-making mode without leading-enterprise dominance or park-management-committee guidance. When $\theta_L < \frac{2D_E + 2D_G}{D_L + 2(D_E + D_G)}$, the overall discounted payoff of the industrial park under the park-management-committee-led mode, V^J , is higher than the overall discounted payoff V^A under the decentralized decision-making mode. For the discounted payoffs of the leading enterprise and park enterprises, V_L^J and V_E^J under the park-management-committee-led mode are higher than V_L^A and V_E^A under the decentralized decision-making mode. When $\theta_L < 1 - \frac{D_L}{2D_G}$, the discounted payoff of the park management committee under the park-management-committee-led mode, V_G^J , is higher than V_G^A under the decentralized decision-making mode.

Proof. According to Equations (5)–(7) and (51)–(53), we obtain $S_G^J - S_G^A = 0$, $S_L^J - S_L^A = \frac{\theta_L \beta \tau D_L}{\mu_L(\xi + \rho)(1 - \theta_L)}$, $\frac{dS_L^J}{d\theta_L} = \frac{\beta \tau D_L}{\mu_L(\xi + \rho)\theta_L^2} > 0$. Moreover, from the proof of Proposition 1, it follows that S is an increasing function of M . since $S_G^H + S_L^H + S_E^H - (S_G^A + S_L^A + S_E^A) = V^J = \frac{\gamma^2 \tau^2 (D_E^2 + 2D_E D_L + 2D_G D_E)}{2(\xi + \rho)^2 \mu_E} + \frac{\alpha^2 \tau^2 (D_G^2 + 2D_G D_L + 2D_G D_E)}{2(\xi + \rho)^2 \mu_G} + \frac{\beta^2 \tau^2 D_E D_L (D_L^2 + 2D_G D_L + 2D_L D_E)}{2(\xi + \rho)^2 (1 - \theta_L) \mu_L} - \frac{\beta^2 \tau^2 D_L^2 \theta_L}{2(\xi + \rho)^2 (1 - \theta_L)^2 \mu_L}$, $\frac{\theta_L \beta \tau D_L}{\mu_L(\xi + \rho)(1 - \theta_L)} > 0$, so $S^J > S^A$. $V^J - V^A = \frac{\theta_L \beta^2 \tau^2 (D_E^2 + 2D_E D_L + 2D_G D_E)(1 - \theta_L) - \beta^2 \tau^2 D_L^2 \theta_L}{2(\xi + \rho)^2 (1 - \theta_L)^2 \mu_L}$, when $\theta_L < \frac{2D_E + 2D_G}{D_L + 2(D_E + D_G)}$, then $V^J - V^A > 0$; $V_G^J - V_G^A = \frac{\theta_L \beta^2 \tau^2 D_L [2(1 - \theta_L) D_G - D_L]}{2(\xi + \rho)^2 (1 - \theta_L)^2 \mu_L}$, when $\theta_L < 1 - \frac{D_L}{2D_G}$, then $V_G^J - V_G^A > 0$; $V_L^J - V_L^A = \frac{\theta_L \beta^2 \tau^2 D_L^2}{2(\xi + \rho)^2 (1 - \theta_L) \mu_L} > 0$, $V_E^J - V_E^A = \frac{\theta_L \beta^2 \tau^2 D_L D_E}{(\xi + \rho)^2 (1 - \theta_L) \mu_L} > 0$.

Thus, the proof is completed. $\square$

5.3. Deep Collaboration Mode

The deep collaboration mode refers to a governance mode in which the park management committee shares the costs incurred by leading enterprises in supporting the work safety improvement of park enterprises, thereby encouraging leading enterprises to continuously strengthen their own work safety management and incentivizing them to share work safety resources with park enterprises. At the same time, relying on their advantages in the field of work safety, leading enterprises make their high-quality work safety resources openly available to park enterprises. Under this mode, the degree of collaboration among the park management committee, leading enterprises, and park enterprises is the strongest, and all three actors jointly devote themselves to improving the work safety level of the industrial park with the objective of maximizing the overall payoff from work safety governance. This mode not only highlights the leading role of the park management committee in promoting work safety, but also reinforces the critical role of leading enterprises in resource sharing and demonstration-based guidance. Accordingly, the objective payoff functions of the park management committee, the leading enterprise, and the park enterprises are given as follows:

$$\pi_G = \int_0^\infty e^{-\rho t} [R(1 - \varepsilon_1 - \varepsilon_2) - \theta_L \frac{\mu_L S_L^2}{2} - \frac{\mu_G S_G^2}{2} - (P - \tau S) D_G] dt \quad (56)$$

$$\pi_L = \int_0^\infty e^{-\rho t} [R\varepsilon_1 - (1 - \theta_L) \frac{\mu_L S_L^2}{2} - (P - \tau S) D_L - \sigma \omega S_E] dt \quad (57)$$

$$\pi_E = \int_0^\infty e^{-\rho t} [R\varepsilon_2 - \frac{\mu_E S_E^2}{2} - (P - \tau S) D_E + \omega S_E] dt \quad (58)$$

Accordingly, under this mode, the optimal strategies of the park management committee, the leading enterprise, and the park enterprises are obtained as follows (denoted by the superscript K):

$$S_G^K = \frac{\alpha \tau D_G}{\mu_G (\xi + \rho)} \quad (59)$$

$$S_L^K = \frac{\beta \tau D_L}{(1 - \theta_L) \mu_L (\xi + \rho)} \quad (60)$$

$$S_E^K = \frac{\omega (\rho + \xi) + \gamma \tau D_E}{\mu_E (\xi + \rho)} \quad (61)$$

Proof. The derivation follows steps similar to those under the decentralized decision-making scenario and is therefore omitted for brevity. $\square$

Under this mode, the optimal payoffs of the park management committee, the leading enterprise, and the park enterprises are respectively given by:

$$V_G^K = \frac{\tau D_G}{\xi + \rho} S^A + \frac{1}{\rho} \left[-PD_G + R(1 - \varepsilon_1 - \varepsilon_2) + \frac{\gamma \tau (\omega + \frac{\gamma \tau D_E}{\xi + \rho}) D_G}{(\xi + \rho) \mu_E} + \frac{\alpha^2 \tau^2 D_G^2}{2(\xi + \rho)^2 \mu_G} \right. \\ \left. + \frac{\beta^2 \tau^2 D_G D_L}{(\xi + \rho)^2 (1 - \theta_L) \mu_L} - \frac{\beta^2 \tau^2 D_L^2 \theta_L}{2(\xi + \rho)^2 (1 - \theta_L)^2 \mu_L} \right] \quad (62)$$

$$V_L^K = \frac{\tau D_L}{\xi + \rho} S^A + \frac{1}{\rho} \left[-PD_L + R\varepsilon_1 - \frac{\omega \sigma (\omega + \frac{\gamma \tau D_E}{\xi + \rho})}{\mu_E} + \frac{\gamma \tau (\omega + \frac{\gamma \tau D_E}{\xi + \rho}) D_L}{(\xi + \rho) \mu_E} \right. \\ \left. + \frac{\alpha^2 \tau^2 D_G D_L}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2 \tau^2 D_L^2}{(\xi + \rho)^2 (1 - \theta_L) \mu_L} \right] \quad (63)$$

$$V_E^K = \frac{\tau D_E}{\xi + \rho} S^A + \frac{1}{\rho} \left[\begin{aligned} & -PD_E + R\varepsilon_2 + \frac{\omega(\omega + \frac{\gamma\tau D_E}{\xi + \rho})}{\mu_E} + \frac{\gamma\tau D_E(\omega + \frac{\gamma\tau D_E}{\xi + \rho})}{(\xi + \rho)\mu_E} \\ & - \frac{(\omega + \frac{\gamma\tau D_E}{\xi + \rho})^2}{2\mu_E} + \frac{\alpha^2\tau^2 D_E D_G}{(\xi + \rho)^2 \mu_G} + \frac{\beta^2\tau^2 D_E D_L}{(\xi + \rho)^2 (1 - \theta_L)\mu_L} \end{aligned} \right] \quad (64)$$

Under the deep collaboration mode, both the work safety level S^K and the discounted total payoff V^K are higher than S^H and V^H under the leading-enterprise-dominated mode, and also higher than S^J and V^J under the park-management-committee-led mode. As for the discounted payoff of park enterprises, V_E^K under the deep collaboration mode is higher than V_E^H under the leading-enterprise-dominated mode. When $\theta_L < 1 - \frac{D_L}{2D_G}$, V_G^K under the deep collaboration mode is higher than V_G^H under the leading-enterprise-dominated mode; when $\theta_L > 1 - \frac{2\beta^2\tau^2\mu_E D_L^2}{1 + 2\sigma\omega[\omega(\xi + \rho)^2 + \gamma\tau D_E(\xi + \rho)]\mu_L}$, V_L^K under the deep col-

laboration mode is higher than V_L^H under the leading-enterprise-dominated mode. For the discounted payoffs of the park management committee and park enterprises, V_G^K and V_E^K under the deep collaboration mode are, respectively, higher than V_G^J and V_E^J under the park-management-committee-led mode. When $\sigma < \frac{\gamma\tau D_L}{\omega(\rho + \xi) + \gamma\tau D_E}$, V_L^K under the deep collaboration mode is higher than V_L^J under the park-management-committee-led mode.

Proof. According to Equations (41)–(43), (50)–(52) and (59)–(61), we obtain $S_G^K - S_G^H = 0$, $S_L^K - S_L^H = \frac{\theta_L \beta \tau D_L}{\mu_L(\xi + \rho)(1 - \theta_L)}$, $S_E^K - S_E^H = 0$, $S_G^K - S_G^J = 0$, $S_L^K - S_L^J = 0$ and $S_E^K - S_E^J = \frac{\gamma\tau D_E}{\mu_E(\xi + \rho)}$. Moreover, from the proof of Proposition 1, it follows that S is an increasing function of M , since $S_G^K + S_L^K + S_E^K - (S_G^H + S_L^H + S_E^H) = \frac{\theta_L \beta \tau D_L}{\mu_L(\xi + \rho)(1 - \theta_L)} > 0$, $S_G^K + S_L^K + S_E^K - (S_G^J + S_L^J + S_E^J) = \frac{\omega}{\mu_E} > 0$, so $S^K > S^H$, $S^K > S^J$. According to Equations (58)–(60), we obtain $V^J = V_G^J + V_L^J + V_E^J$, that is $V^J = \frac{\gamma^2\tau^2(D_E^2 + 2D_E D_L + 2D_G D_E)}{2(\xi + \rho)^2 \mu_E} + \frac{\alpha^2\tau^2(D_G^2 + 2D_G D_L + 2D_G D_E)}{2(\xi + \rho)^2 \mu_G} + \frac{\beta^2\tau^2 D_E D_L(D_L^2 + 2D_G D_L + 2D_L D_E)}{2(\xi + \rho)^2 (1 - \theta_L)\mu_L} - \frac{\beta^2\tau^2 D_L^2 \theta_L}{2(\xi + \rho)^2 (1 - \theta_L)^2 \mu_L}$, $V^K - V^J = \frac{\gamma\tau\omega(D_G + D_L)}{(\xi + \rho)\mu_E} + (\frac{1}{2} - \sigma)\omega^2 + (1 - \sigma)\frac{\omega\gamma\tau D_E}{\xi + \rho} > 0$; $V^K - V^H = \frac{\theta_L \beta^2\tau^2 D_L(D_G + D_E)}{1 - \theta_L} + (1 - \sigma)\omega\frac{(\omega + \frac{\gamma\tau D_E}{\xi + \rho})}{\mu_E} + \frac{\beta^2\tau^2 D_L^2}{2(\xi + \rho)^2 (1 - \theta_L)} > 0$. $V_G^K - V_G^H = \frac{\beta^2\tau^2 D_L \theta_L [2(1 - \theta_L)D_G - D_L]}{2(\xi + \rho)^2 (1 - \theta_L)^2 \mu_L}$. When $\theta_L < 1 - \frac{D_L}{2D_G}$, then $V_G^K > V_G^H$; $V_L^K - V_L^H = -\frac{\omega(\omega + \frac{\gamma\tau D_E}{\xi + \rho})}{\mu_E} + (\frac{1}{1 - \theta_L} - \frac{1}{2})\frac{\beta^2\tau^2 D_L^2}{(\xi + \rho)^2 \mu_L}$. When $\theta_L > 1 - \frac{2\beta^2\tau^2\mu_E D_L^2}{1 + 2\sigma\omega[\omega(\xi + \rho)^2 + \gamma\tau D_E(\xi + \rho)]\mu_L}$, then $V_L^K > V_L^H$; $V_E^K - V_E^H = \frac{\omega[\omega(\xi + \rho) + \gamma\tau D_E]}{\mu_E(\xi + \rho)} + \frac{\theta_L \beta^2\tau^2 D_L D_E}{(1 - \theta_L)(\xi + \rho)^2 \mu_L} > 0$; $V_G^K - V_G^J = \frac{\gamma\tau\omega D_G}{(\xi + \rho)\mu_E} > 0$; $V_L^K - V_L^J = \frac{\omega[\gamma\tau(D_L - \sigma D_E) - \sigma\omega(\xi + \rho)]}{(\xi + \rho)\mu_E}$, when $\sigma < \frac{\gamma\tau D_L}{\omega(\xi + \rho) + \gamma\tau D_E}$, then $V_L^K - V_L^J > 0$; $V_E^K - V_E^J = \frac{\omega^2}{2\mu_E} + \frac{\gamma\tau\omega D_E}{(\xi + \rho)\mu_E} > 0$.

Thus, the proof is completed. $\square$

6. Numerical Analysis

Based on the analytical results of the above model, numerical simulation is conducted in MATLAB R2016b to enable a more intuitive and in-depth investigation. To ensure the accuracy and reliability of the study, this research was informed by an in-depth investigation of an industrial park in Zhenjiang, Jiangsu Province. Based on the actual operational characteristics of the park management committee, leading enterprises, and park enterprises in work safety governance, consultations and discussions were conducted with relevant experts regarding the parameter settings. Since the objective of the numerical simulation is to reveal the dynamic evolution characteristics under different reciprocal symbiosis modes, the parameter values mainly reflect the relative relationships among variables rather than precise empirical observations. Following the parameter-setting approaches adopted by Yin et al. [63], Li et al. [64], and Ding et al. [69], the exogenous parameters were appropriately

assigned and simplified according to the practical context. Accordingly, the parameter values are determined with reference to the literature and practical conditions as follows: $\xi = 0.3$, $\rho = 0.5$, $\alpha = 0.5$, $\beta = 0.5$, $\gamma = 0.5$, $D_G = 800$, $D_E = 800$, $D_L = 1200$, $\tau = 0.002$, $\mu_G = 5$, $\mu_L = 10$, $\mu_E = 5$, $R = 80$, $\varepsilon_1 = 0.65$, $\varepsilon_2 = 0.2$, $\sigma = 0.2$, $S_0 = 1$.

6.1. Changes in the Work Safety Level of the Industrial Park and the Payoffs of Symbiotic Units Under the Leading-Enterprise-Dominated Mode

When the resource-sharing coefficient of the leading enterprise is set at 1, 3, 5, and 7, respectively, the changes in the work safety level of the industrial park are shown in Figure 1a. Figure 1b–d present the changes in the payoffs of the symbiotic units in the industrial park symbiotic system under different resource-sharing coefficients.

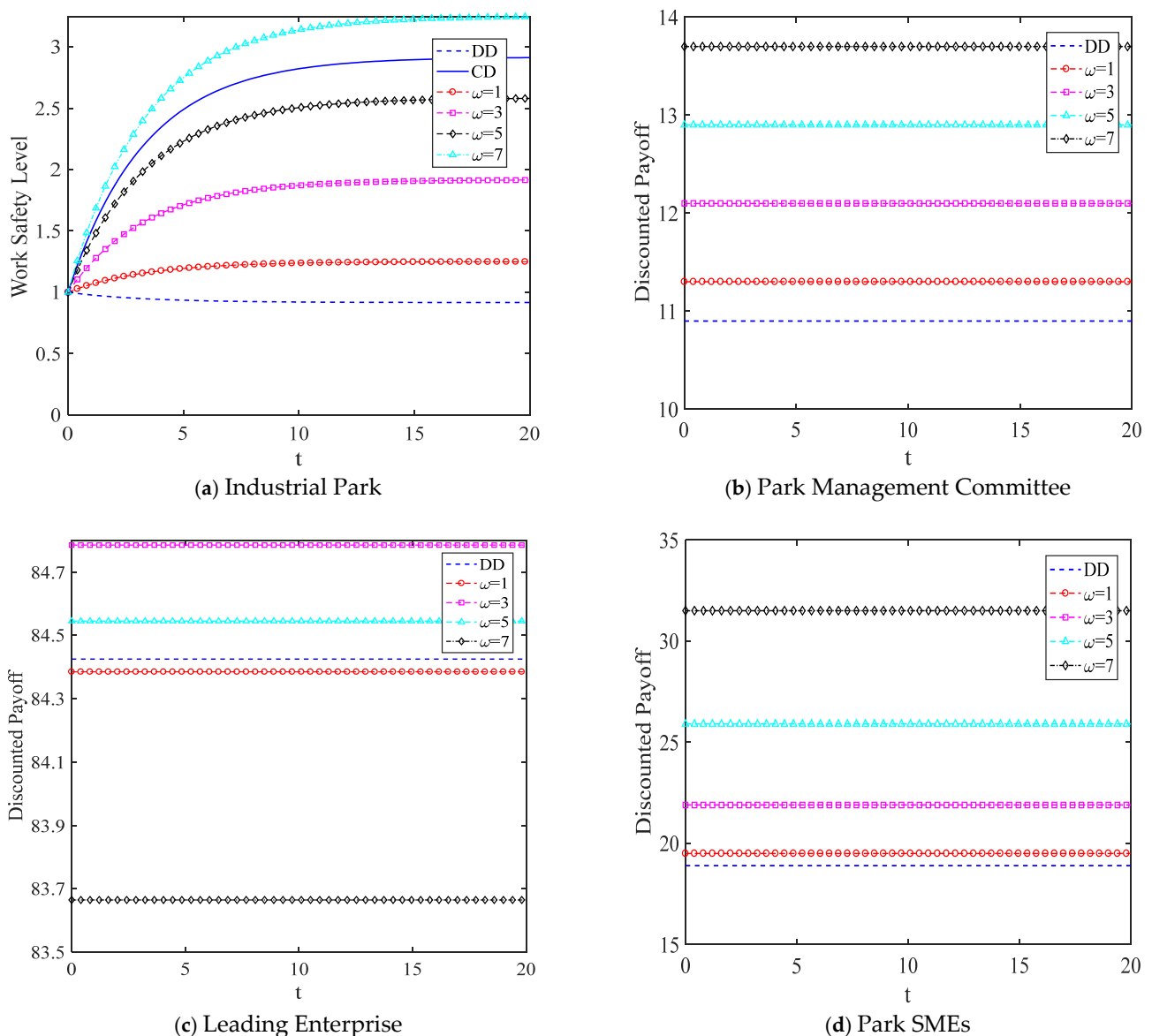


Figure 1. Changes in the level of safety and the benefits of symbiotic units in the park under the model dominated by the leading firms. Note: DD = Decentralized Decision-Making, CD = Centralized Decision-Making.

As shown in Figure 1a, with the increase in the leading enterprise's work safety resource-sharing coefficient, the work safety level of the industrial park also exhibits an upward trend. A comparison of the park's work safety levels under different modes

indicates that both the centralized decision-making mode and the leading-enterprise-dominated mode yield higher work safety levels than the decentralized decision-making mode. Moreover, when the leading enterprise's resource-sharing coefficient exceeds a certain threshold, the park's work safety level under the leading-enterprise-dominated mode becomes higher than that under the centralized decision-making mode. This does not mean that the former is economically superior. Centralized decision-making maximizes the total system payoff by balancing safety benefits against safety effort, resource-sharing, and other governance costs; therefore, it yields an economically optimal rather than technically maximal safety level. In contrast, although a high resource-sharing coefficient may further improve the park's work safety level, it may also increase the resource-sharing costs borne by the leading enterprise and other related governance costs. Therefore, the higher work safety level resulting from excessive resource sharing may be achieved at the expense of overall economic efficiency. Figure 1b shows that, under the leading-enterprise-dominated mode, the discounted payoff of the park management committee is higher than that under decentralized decision-making, and it increases as the leading enterprise's resource-sharing coefficient rises. As can be seen from Figure 1c, within a relatively low range of the resource-sharing coefficient, the discounted payoff of the leading enterprise exhibits an increasing trend. However, as the resource-sharing coefficient continues to increase and reaches a certain threshold, the leading enterprise's payoff begins to decline. When the resource-sharing coefficient becomes relatively large, the discounted payoff of the leading enterprise falls below that under the decentralized decision-making mode. Figure 1d indicates that, as the intensity of resource sharing by the leading enterprise increases, the discounted payoff of park enterprises shows an increasing trend, suggesting that the marginal effect of the resource-sharing coefficient on improving the discounted payoff of park enterprises is increasing. In addition, under the leading-enterprise-dominated mode, the discounted payoff of park enterprises is higher than that under the decentralized decision-making mode.

6.2. Changes in the Work Safety Level of the Industrial Park and the Payoffs of Symbiotic Units Under the Park-Management-Committee-Led Mode

When the cost-sharing coefficient of the park management committee is set at 0.1, 0.3, 0.5, and 0.7, respectively, the changes in the work safety level of the industrial park are shown in Figure 2a. Figure 2b–d present the changes in the payoffs of the symbiotic units in the industrial park symbiotic system under different cost-sharing coefficients.

As shown in Figure 2a, the work safety level of the industrial park increases as the cost-sharing coefficient of the park management committee rises. A comparison across different modes indicates that both the centralized decision-making mode and the park-management-committee-led mode generate higher work safety levels than the decentralized decision-making mode. Moreover, when the cost-sharing coefficient exceeds a certain threshold, the work safety level under the park-management-committee-led mode becomes higher than that under the centralized decision-making mode. Figure 2b shows that, under the park-management-committee-led mode, the discounted payoff of the park management committee decreases as its cost-sharing coefficient increases, and when the cost-sharing coefficient exceeds 0.3, its discounted payoff falls below that under the decentralized decision-making mode. As can be seen from Figure 2c, when the cost-sharing ratio of the park management committee remains at a relatively low level, the discounted payoff of the leading enterprise is slightly higher than that under the decentralized decision-making mode. As the cost-sharing coefficient of the park management committee increases, the marginal effect on the discounted payoff of the leading enterprise exhibits an increasing trend. Figure 2d indicates that, under the park-management-committee-led mode, the discounted payoff of park enterprises is significantly higher than that under the decentralized

decision-making mode. Moreover, as the cost-sharing coefficient of the park management committee increases, the discounted payoff of park enterprises also shows a trend of increasing marginal gains.

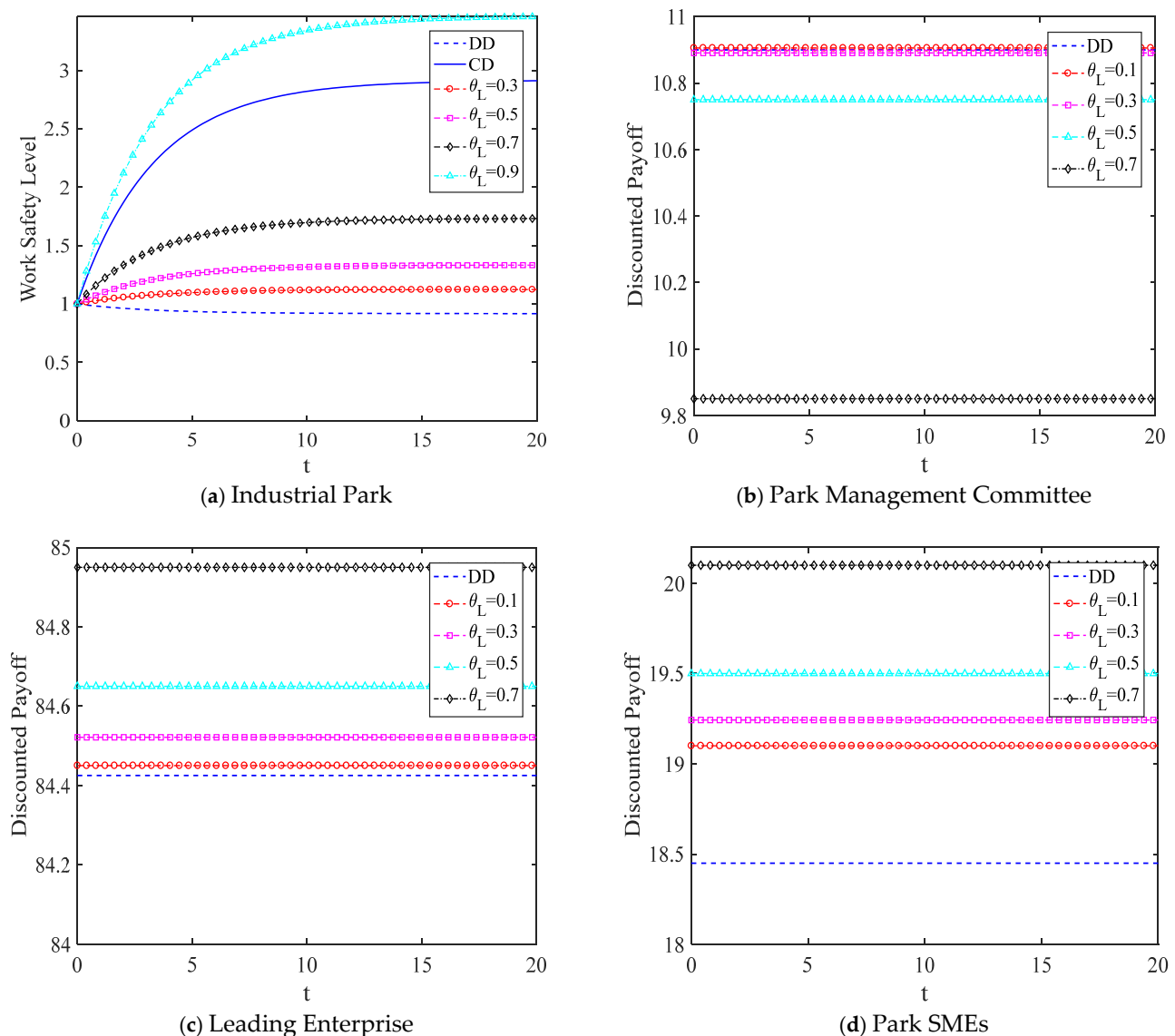


Figure 2. Changes in the level of safety in the park and the benefits of symbiotic units under the traction model of the park management committee.

6.3. Changes in the Total Payoff of the Industrial Park Under the Deep Collaboration Mode

When the resource-sharing coefficient is set at 1, 3, 5, and 7, respectively, the changes in the discounted total payoff of the industrial park symbiotic system are shown in Figure 3a. When the cost-sharing coefficient is set at 0.1, 0.3, 0.5, and 0.7, respectively, the changes in the discounted total payoff of the industrial park symbiotic system are shown in Figure 3b.

As shown in Figure 3a, the discounted total payoff of the industrial park under the deep collaboration mode is much higher than that under the decentralized decision-making mode. When the resource-sharing coefficient is held constant, the discounted total payoff of the industrial park under the deep collaboration mode is higher than that under the leading-enterprise-dominated mode. Moreover, as the resource-sharing coefficient increases, the total payoff of the park under the deep collaboration mode exhibits a clear upward trend. This indicates that, when resource sharing is more adequate, the deep collaboration mode is better able to tap and utilize resource potential, thereby promoting the growth of the

park's total payoff. As shown in Figure 3b, when the cost-sharing coefficient is held constant, the discounted total payoff of the industrial park under the deep collaboration mode is significantly higher than that under the park-management-committee-led mode. This suggests that, under the same cost-sharing coefficient, the deep collaboration mode has a more pronounced advantage in terms of discounted total payoff than the park-management-committee-led mode. In addition, compared with the sensitivity of total payoff to the resource-sharing coefficient, the discounted total payoff of the industrial park also shows an increasing trend as the cost-sharing ratio gradually rises, but its sensitivity is relatively lower and the increase is more moderate.

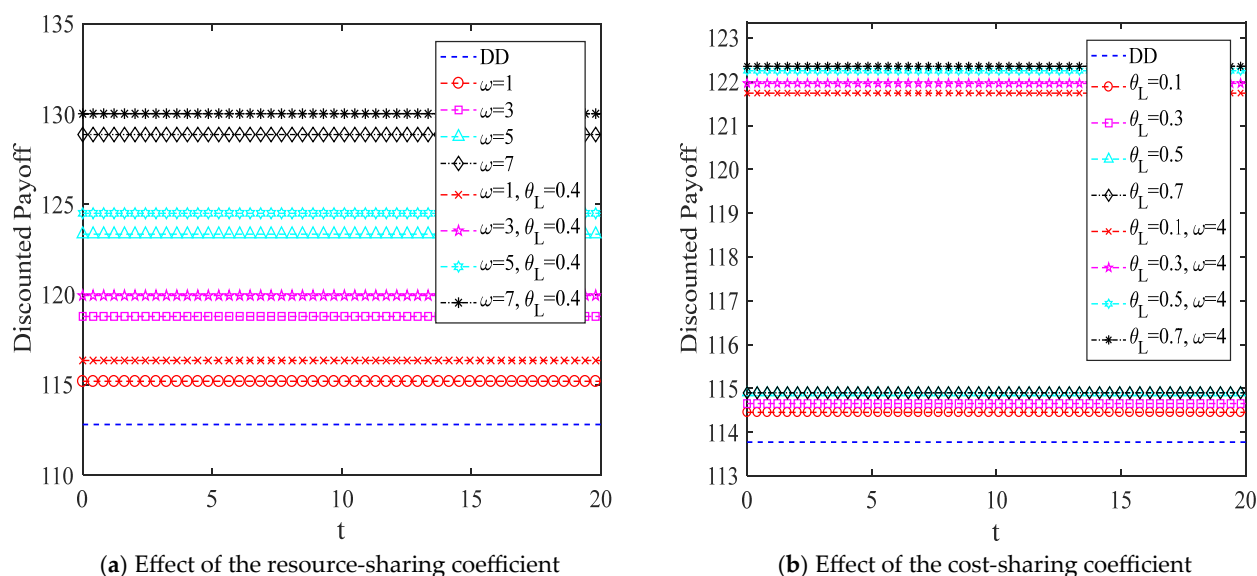


Figure 3. Impact of resource sharing and cost-sharing coefficients on total returns of industrial parks under the deep collaboration model.

7. Discussion

This study constructs a differential game model for the collaborative governance of work safety in industrial parks from the perspective of reciprocal symbiosis, and compares the dynamic evolution of multi-agent behavioral decisions and governance performance under different reciprocal symbiosis modes. The research findings further clarify the internal mechanism linking resource sharing, cost sharing and collaborative governance, and offer new theoretical insights into multi-stakeholder collaborative governance within industrial parks.

First, continuous improvement in the work safety resource sharing level of leading enterprises can effectively raise the overall work safety level and total benefits of industrial parks. This result confirms the general consensus on resource sharing and collaborative governance established in existing literature. Previous studies have demonstrated that leading enterprises can enhance the capacity of upstream and downstream firms along the industrial chain via technology spillover, knowledge sharing and management experience transfer, thus improving the overall governance efficiency and operational resilience of the industrial system [20,21,70]. Nevertheless, existing research mainly focuses on the positive governance effects brought by resource sharing, while paying insufficient attention to how stakeholders' benefits change as resource sharing expands continuously. This study further finds that once the intensity of resource sharing exceeds a certain threshold, the discounted payoffs of leading enterprises begin to decline, whereas the payoffs of the park management committee and resident enterprises keep rising. This indicates that leading enterprises face obvious diminishing marginal returns in work safety resource sharing.

Expanding resource sharing continuously leads to rising costs alongside slowing revenue growth, which explains why some leading enterprises lack enthusiasm for resource sharing in practice.

Second, raising the cost-sharing ratio of the park management committee can effectively elevate the overall work safety level of the industrial park and increase the discounted payoffs of leading enterprises and resident enterprises. Existing studies suggest that the government can reduce enterprises' work safety investment costs and strengthen their willingness to fulfill work safety responsibilities through financial subsidies, cost sharing and institutional incentives, so as to improve overall governance performance [69,71]. Nevertheless, most scholars emphasize the positive effects of financial support while neglecting the rising governance costs caused by continuous growth of public investment. This study further reveals that the discounted payoffs of the park management committee keep declining as the cost-sharing ratio rises. Once the ratio exceeds a certain threshold, its payoffs will even fall below the level under the decentralized decision-making mode. This indicates that higher financial input does not always yield better outcomes. Work safety governance in industrial parks should attach importance to fiscal sustainability and strike a reasonable balance between governance performance and public investment.

Third, among the three reciprocal symbiosis modes, the deep coordination mode achieves the highest overall benefits and work safety level for the industrial park. This finding further supports the viewpoint of collaborative governance theory that multi-stakeholder cooperation outperforms independent governance by a single actor. Existing studies generally hold that multi-agent collaboration facilitates resource sharing, risk pooling and complementary advantages, and enhances the overall governance capacity of complex systems [43,44]. However, most prior literature only discusses static collaborative relationships and lacks dynamic explanations of how stakeholders build stable partnerships through long-term interaction. Based on reciprocal symbiosis theory, this study constructs a differential game model and further reveals the positive feedback dynamic mechanism formed by institutional provision from the park management committee, resource sharing by leading enterprises, and active responsibility fulfillment by resident enterprises. It demonstrates that high work safety governance performance relies on continuous complementary advantages among stakeholders and the ongoing optimization of benefit coordination mechanisms.

Finally, compared with previous studies on safety governance using static games or evolutionary games, this paper adopts a differential game framework and treats the work safety level of industrial parks as a continuously evolving state variable, which better reflects the long-term and progressive nature of real-world work safety governance. In addition, work safety facilities, technical capacity and safety capital continuously accumulate and depreciate throughout the governance process, and differential game theory can effectively capture such continuous dynamic changes [72]. Nevertheless, the collaborative governance mode proposed in this study still faces obstacles in practical implementation. Economically, sustained resource sharing and cost sharing require long-term benefit compensation mechanisms and stable fiscal guarantee systems. Technically, digital information platforms, work safety data sharing systems and dynamic performance evaluation frameworks are essential to provide technical support for continuous multi-stakeholder collaboration.

8. Conclusions and Implications

8.1. Conclusions

Based on the dynamic evolution of the work safety level in industrial parks over time, this study constructs a differential game model to systematically analyze the changes in

work safety effort levels, discounted payoffs, and the overall work safety level of the park under different decision-making mechanisms and reciprocal symbiosis modes involving the park management committee, leading enterprises, and park enterprises. The results show that:

- (1) Compared with the decentralized decision-making mode, the leading-enterprise-dominated mode can improve the overall payoff of the industrial park. Under this mode, the overall work safety level of the park increases with the rise in the leading enterprise's work safety resource-sharing coefficient. For the leading enterprise itself, however, its discounted payoff increases when the resource-sharing coefficient is relatively low, but begins to decline once the coefficient exceeds a certain threshold; at a relatively high level of resource sharing, its discounted payoff may even fall below that under the decentralized decision-making mode. In contrast, the discounted payoffs of the park management committee and park enterprises increase with the strengthening of resource sharing by the leading enterprise.
- (2) Under the park-management-committee-led mode, the overall discounted payoff of the industrial park is higher than that under the decentralized decision-making mode, and the park's work safety level improves as the cost-sharing coefficient of the park management committee increases. However, the discounted payoff of the park management committee declines with the increase in the cost-sharing coefficient, and when this coefficient exceeds a certain level, its discounted payoff becomes lower than that under the decentralized decision-making mode. By contrast, the discounted payoffs of both the leading enterprise and the park enterprises exhibit increasing marginal gains as the cost-sharing coefficient of the park management committee rises.
- (3) Under the deep collaboration mode, the discounted total payoff of the industrial park is far higher than that under the decentralized decision-making mode. When either the resource-sharing coefficient or the cost-sharing coefficient is held constant, the discounted total payoff of the industrial park under the deep collaboration mode is higher than that under both the leading-enterprise-dominated mode and the park-management-committee-led mode. Moreover, as the resource-sharing coefficient and the cost-sharing coefficient increase, the total payoff of the park under the deep collaboration mode shows a clear upward trend. In addition, compared with the sensitivity of total payoff to the cost-sharing coefficient, the resource-sharing coefficient has a more pronounced effect on the increase in the discounted total payoff of the industrial park.

Overall, these findings indicate that the improvement of work safety in industrial parks is not determined by the behavior of any single actor, but by the dynamic interaction among multiple interdependent actors within the park system. From a sustainable development perspective, improving the work safety level of an industrial park should not rely solely on continuously increasing governance inputs; rather, it requires a system-wide balance among safety performance, economic efficiency, the sustainability of resource sharing, and the long-term stability of collaborative relationships.

8.2. Implications

This paper gives the following management implications:

First, greater effort should be made to encourage and support leading enterprises within industrial parks to fully leverage their leadership and spillover effects in work safety governance, thereby promoting the orderly sharing of advanced safety management systems, technical equipment, training resources, and governance experience across the park, and enhancing both the overall work safety level and the collaborative governance capacity

of the park. In sustainable industrial parks, leading enterprises are not only organizers of industrial chains but also important carriers for the diffusion of safety resources and the spillover of governance capabilities. Therefore, governments and park management committees may adopt policy instruments such as tax incentives, special subsidies, and demonstration-project recognition to strengthen the willingness of leading enterprises to participate in resource sharing. At the same time, a dynamic benefit compensation mechanism should be established. When the intensity of resource sharing exceeds a certain threshold and the marginal benefit of the leading enterprise declines, appropriate compensation may be provided through preferential benefit distribution, fiscal subsidies, or cost-sharing arrangements, so as to sustain the endogenous motivation of leading enterprises to continue participating in collaborative park governance. Such measures would not only help release the technological spillover effects of leading enterprises, but also improve the overall governance efficiency and sustainable operational capacity of industrial parks.

Second, the park management committee should establish a differentiated cost-sharing mechanism aligned with the park's development stage, risk level, and governance performance, so as to better perform its institutionally guiding role in collaborative work safety governance. At the early stage of park development, when park enterprises generally have weak safety foundations and insufficient governance capacity, the committee may strengthen incentives for safety investment through a relatively high cost-sharing ratio, thereby helping enterprises pass through the capability-building stage. Once the park becomes relatively mature, the cost-sharing ratio may be gradually reduced in light of improved enterprise profitability, changes in risk levels, and enhanced governance performance, thus promoting a shift in governance responsibility from external support to internally driven improvement. In addition, it would be worthwhile to explore the establishment of a "risk-sharing fund" or a "work safety governance fund" jointly participated in by the park management committee, leading enterprises, and park enterprises, thereby forming a stable and sustainable cost-sharing mechanism. Such arrangements would strengthen the park's ability to withstand risk shocks, reduce the systemic losses caused by accidents, and promote the coordinated improvement of safety performance and economic performance.

Third, active efforts should be made to promote a higher level of deep collaboration among the park management committee, leading enterprises, and park enterprises, so as to build a multi-actor community for work safety governance. Compared with governance led by a single actor, deep collaboration is more conducive to achieving the optimal allocation of resources, the rational sharing of costs, and the improvement of overall performance. In practice, digital platforms—such as shared equipment management systems, safety data middle platforms, and intelligent early-warning platforms—can be utilized to reduce the marginal costs of safety resource sharing and collaborative governance while improving the efficiency of information flows and collaborative responses. At the same time, a dynamic adjustment mechanism linking cost-sharing ratios to park safety performance may be established, so as to organically connect the input responsibilities of the park management committee, leading enterprises, and park enterprises with governance outcomes, thereby enhancing the incentive compatibility of collaborative governance. In addition, industrial parks may further explore emerging digital technologies to improve the transparency of governance processes and information sharing efficiency. Through these measures, work safety governance in industrial parks can be shifted from fragmented responses toward systemic collaboration, thereby enhancing the system resilience, sustainable operational capacity, and overall sustainable development level of industrial parks.

8.3. Limitations and Future Study

Although this study, based on symbiosis theory and differential game methods, explores the behavioral choices of the park management committee, leading enterprises, and park enterprises in collaborative work safety governance under different reciprocal symbiosis modes, as well as their effects on the overall performance of the industrial park, several limitations remain and warrant further investigation in future research.

First, the model constructed in this study mainly focuses on three core actors—the park management committee, leading enterprises, and park enterprises—which helps reveal the interaction relationships among the principal stakeholders within industrial parks. However, insufficient attention is paid to the roles of external actors such as government regulatory authorities and third-party work safety service institutions. Future research may therefore further broaden the analytical scope by incorporating a wider range of governance actors into a unified framework, thereby developing a multi-actor collaborative governance model that better reflects real-world conditions. Second, this study mainly focuses on the resource-sharing coefficient and the cost-sharing coefficient, with particular emphasis on the changing patterns of work safety levels and discounted payoffs under different reciprocal symbiosis modes. For sustainable industrial parks, however, work safety is not only related to accident prevention and economic returns, but is also closely associated with system resilience, resource-use efficiency, environmental risk prevention, and long-term operational stability. Owing to the need to maintain analytical tractability, these dimensions have not yet been systematically incorporated into the model. Future research may introduce indicators such as environmental performance, operational resilience, and resource allocation efficiency, so as to deepen the investigation of the coupling relationship between work safety governance and the sustainable development of industrial parks. Third, to focus on the strategic interactions among the park management committee, leading enterprises, and park enterprises, this study assumes that the park management committee can determine the cost-sharing coefficient without explicit budget constraints. In practice, however, public governance entities are often subject to fiscal limitations and competing expenditure priorities. As a result, the incentive capacity of the park management committee may be weaker than that predicted by the model when available financial resources are constrained. Future research could incorporate budget ceilings or dynamic fiscal constraints into the differential game framework to further examine how public financial capacity affects the effectiveness of collaborative work safety governance and the evolution of reciprocal symbiosis modes. Fourth, the differential game model developed in this study is based on a deterministic framework and assumes that the evolution of the industrial park's work safety level follows a predictable dynamic trajectory. However, real-world work safety governance is often affected by unexpected events, rare accidents, policy adjustments, and external environmental shocks, all of which may introduce significant uncertainty into the governance process. As a result, the deterministic differential game framework may have limitations in capturing sudden safety shocks and stochastic risk fluctuations. Future research could extend the present model by incorporating stochastic disturbance terms and developing a stochastic differential game framework, thereby providing a more realistic representation of the dynamic interactions among governance actors under uncertain work safety environments.

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