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Incentive Mechanism of Construction Safety from the Perspective of Mutual Benefit

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Abstract: Improving the level of construction safety is an important task for stakeholders. How to balance the interests and reduce the conflicts between stakeholders has become the key factor in reducing accidents. To design incentive mechanisms that can not only improve the level of construction safety but also make the construction enterprise and construction workers mutually beneficial, differential game models under different incentive mechanisms are constructed. The study found that the greater the impact of construction workers' safety efforts on the safety reward and punishment, the higher the level of construction safety. However, when construction workers' efforts have too much impact on the reward and punishment, it is not conducive to the improvement of the income of the construction enterprise. The smaller the proportion of income allocated to the construction enterprise, the higher the level of construction safety. However, when the proportion of income obtained by the construction enterprise is too low, it is not conducive to the improvement of the income of the construction enterprise. The safety reward and punishment mechanism and the income sharing mechanism that meet specific conditions can make the construction enterprise and construction workers mutually beneficial. In addition, the level of construction safety and the income of the construction enterprise and construction workers under the combination mechanism composed of the reward and punishment mechanism and the income sharing mechanism is higher than that under a single mechanism.

Keywords: construction safety; mutual benefit; differential game; reward and punishment; income sharing

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1. Introduction

Sustainability and safety are two issues that have attracted more attention in the construction field [1,2]. In construction safety, construction enterprises have conducted a lot of work, such as improving the construction environment of construction workers, strengthening safety management, and so on. However, the construction industry is still a high-risk industry [3]. The construction industry's share of fatalities is the highest of all industries, accounting for roughly 19% of all workplace fatalities, although the industry accounts for roughly 4.5% of the total workforce [3]. Therefore, the safety performance of the construction industry is still an area of concern.

There are many factors affecting construction safety [2–5], among which the safety management behaviour of construction enterprises and the safety behaviour of construction workers are two important factors [6–11]. The improvement in the level of construction safety is the result of the joint efforts of construction enterprises and construction workers. In the process of construction, the construction enterprise and its construction workers are interdependent. The survival of the construction enterprise depends on the labour paid by its construction workers, and the survival of construction workers depends on the wages paid by the construction enterprise. This is consistent with the symbiosis theory in ecology. The system of construction safety can be regarded as a symbiotic system. As an epistemology and methodology, symbiosis theory has been applied in many fields [12–16]. According to symbiosis theory, the symbiotic system has higher efficiency and stability under the mutually beneficial mode [17–21]. The mutually beneficial mode can balance the interests and reduce the conflicts between the construction enterprise and construction workers. How to balance the interests and reduce the conflicts between the stakeholders of construction safety is the key factor to reduce accidents [22]. Therefore, it is necessary to design incentive mechanisms of construction safety from the perspective of mutual benefit.

Reward and punishment is a common mechanism to encourage construction workers to take safety behaviour. At present, there are many studies on the impact of the reward and punishment mechanism on workers' safety behaviour. Ting pointed out that punishment can make front-line workers adopt safety behaviour [23]. Guo found that rewards can strengthen construction workers' safety behaviour, and punishment can inhibit the occurrence of unsafe behaviour [24]. Shin found that rewards could encourage construction workers to adopt safety behaviour [25]. Because safety behaviour requires construction workers to expend more effort, rational construction workers will compare rewards and punishments with their efforts before taking action. According to Becker's related research [26], when the expected cost is less than the expected benefit, their behaviour motivation will be transformed into real behaviour. Thus, too low rewards and punishments cannot play an incentive role. Excessive reward and punishment will reduce the income of construction enterprises or construction workers. How to make the reward and punishment mechanism not only improve the level of construction safety but also improve the income of construction enterprises and construction workers is still a gap in the relevant research.

Revenue sharing is a mechanism used to solve the problem of supply chain coordination in supply chain management. Supply chain management has a mature body of knowledge [27]. Some coordination mechanisms in supply chain management, such as revenue sharing mechanisms and cost sharing mechanisms, have been used to improve the safety level of production in supply chains. For example, Yang founded that the revenue sharing mechanism and the cost sharing mechanism can improve the safety level of production in the supply chain composed of suppliers and manufacturers [28]. Can the revenue sharing mechanism or the income sharing mechanism improve the safety level of the system composed of construction enterprises and construction workers? What kind of income sharing mechanism can improve the income of construction enterprises and construction workers at the same time? Can the combination of reward and punishment mechanism and income sharing mechanism bring a higher safety level? These problems lack relevant research.

Reward and punishment mechanism and income sharing mechanism will affect the income of the construction enterprise and construction workers. Driven by interest, they will have a behavioural interaction. This behaviour interaction can be analysed by the evolutionary game theory [22]. Evolutionary game theory has been widely used in the research of traffic safety [29–31], food safety [32–34], coal mine safety [35–37], construction safety [38–42], and so on. For example, Yun established an evolutionary game model to analyse the safety strategy selection of stakeholders in the tower crane operation on construction sites [6]. Guo used evolutionary game theory to analyse the impact of different behaviour strategies among the government, construction units, and construction workers on the behaviour strategies of other parties [41].

However, the above research did not consider the dynamic change characteristics of the level of construction safety. The level of construction safety will change dynamically with time under the influence of factors such as aging of construction equipment and facilities. This change will affect the decision making of the construction enterprise and construction workers in the game of construction safety. Evolutionary game theory cannot analyse the game behaviours of the construction enterprise and construction workers in this situation. However, the differential game theory can. The differential game refers to the continuous game of multiple participants in a time-continuous system trying to optimize their independent and conflicting goals and finally obtain the strategies of each participant over time and achieve a Nash equilibrium [43–45]. Based on differential game theory, the following work is performed: (1) The differential game model without incentive mechanism, the differential game model under the safety reward and punishment mechanism, and the differential game model under the income sharing mechanism are constructed; (2) the safety efforts and the income of the construction enterprise and construction workers under different mechanisms are compared; (3) safety incentive mechanisms are designed, which can not only improve the level of construction safety but can also make the construction enterprise and construction workers mutually beneficial.

The remainder of the research is structured as follows. In the second section, differential game models under different situations are established and solved. The third section compares the model results and analyses the influence of the main parameters on the model results through a numerical example. The fourth part is the conclusion and suggestion.

2. Model Construction and Solution

2.1. Differential Game Theory

The differential game can be regarded as a generalization of optimal control theory and dynamic programming in which more than one player is involved in the game [44]. The differential game is defined as follows:

In a differential game with n participants, the strategy chosen by the participant i at time t is $u_i(t)$, then his objective function in the game period $[t_0, T]$ is:

$$\max_{u_i} \int_{t_0}^{T} g_i(t, x(t), u_1(t), u_2(t), \ldots, u_n(t))dt + Q_i(x(T)) \tag{1}$$

where $g_i(t, x, u_1, u_2, \ldots, u_n)$ represents the payment of participant i at time t, and the payment result is consistent with the strategic behaviours of other participants at time t. It is also related to the state variable $x(t)$. At the end of the game period, the terminal return of participant i is related to the state variable $x(T)$ at that time, which is $Q_i(x(T))$. The state variable $x(t)$ satisfies the following dynamic variation equation:

$$\dot{x}(t) = f(t, x(t), u_1(t), u_2(t), \ldots, u_n(t)),\ x(t_0) = x_0 \tag{2}$$

where $\dot{x}(t) = dx(t)/dt$. $g_i(t, x, u_1, u_2, \ldots, u_n)$ and $f(t, x, u_1, u_2, \ldots, u_n)$ are differentiable. The optimal strategy set of all participants except participant i is $u^*_{-i} = \{u_1^*, u_2^*, \ldots u_{i-1}^*, u_{i+1}^*, \ldots, u_n^*\}$. If there is $\int_{t_0}^{T} g_i(t, x(t), u_i^*(t), u^*_{-i}(t))dt + Q_i(x(T)) \geq \int_{t_0}^{T} g_i\left(t, x^{[i]}(t), u_i(t), u^*_{-i}(t)\right)dt + Q_i\left(x^{[i]}(T)\right)$ for all u_i^*, then the strategy set $(u_1^*, u_2^*, \ldots, u_n^*)$ is said to constitute a non-cooperative Nash equilibrium solution of differential game involving n people, where $x(t)$ and $x^{[i]}(t)$ represent the state when the participant i selects the optimal strategy and does not select the optimal strategy in the period $[t_0, T]$. $x(t)$ and $x^{[i]}(t)$ satisfy:

$$\dot{x}(t) = f(t, x(t), u_i^*(t), u^*_{-i}(t)),\ x(t_0) = x_0 \tag{3}$$

$$\dot{x}^{[i]}(t) = f\left(t, x^{[i]}(t), u_i^*(t), u^*_{-i}(t)\right), x(t_0) = x_0 \tag{4}$$

The Nash equilibrium solution of the differential game can be obtained by constructing Hamilton Jacobi Bellman equation (HJB) [46–48].

2.2. Model Symbols

The symbols used in the model are shown in Table 1.

Table 1. Model symbols.

Model Symbols	Meaning
π_E	Construction enterprise's income function.
π_W	Construction workers' income function.
$S(t)$	Level of construction safety at time t.
S_E	Construction enterprise's safety effort.
S_W	Construction workers' safety effort.
k_E	Cost coefficient of construction enterprise's safety effort.
k_W	Cost coefficient of construction workers' safety effort.
α	Influence coefficient of construction enterprise's safety effort on the level of construction safety.
β	Influence coefficient of construction workers' safety efforts on the level of construction safety.
δ	Attenuation rate of the level of construction safety.
I	Construction enterprise's income other than safety effort costs, accident losses, and construction workers' salaries.
W	Salary received by construction workers without safety reward and punishment.
L	Maximum punishment to construction workers.
μ	Coefficient of safety reward and punishment.
P	Accident probability under unsafe conditions.
ε	Influence coefficient of safety level on accident probability.
L_E	Loss of the construction enterprise in the case of accident.
L_W	Loss of construction workers in the case of accident.
ρ	Discount rate.
d_E	Proportion of income obtained by the construction enterprise under the income sharing mechanism.
d_W	Proportion of income obtained by construction workers under the income sharing mechanism.
N	Situation without safety incentive mechanism.
R	Situation with the reward and punishment mechanism.
C	Situation with the income sharing contract
RC	Situation with the joint action of the reward and punishment mechanism and the income sharing mechanism

2.3. Model Assumptions

Hypothesis 1. The participants in the game are a construction enterprise and its construction workers. Efforts of the construction enterprise in safety equipment investment, safety supervision, and other work related to construction safety are called the safety effort of the construction enterprise. Efforts of construction workers in complying with the safety system and other work related to construction safety are called the safety effort of construction workers.

Hypothesis 2. According to the convexity characteristic of cost [49–51], the costs of the construction enterprise's safety effort and construction workers' safety effort are ${k_E}'{S_E}^2/2$ and $k_w {S_w}^2/2$, respectively, where ${k_E}'$ is the cost coefficient of construction enterprise's safety effort without considering the impact of safety investment on production investment. S_E is the safety effort of the construction enterprise. k_w is the cost coefficient of the safety effort of construction workers. S_w is the safety effort of construction workers. The increase in safety investment may lead to the decrease in production investment, resulting in opportunity loss. To ensure that I in Table 1 does not change with the level of construction safety, it is assumed that the opportunity loss generated by the construction enterprise's safety effort is $-{k_E}''{k_E}'{S_E}^2/2$, where ${k_E}''$ is the impact coefficient of safety effort on the construction enterprise's production income. Taking into account the opportunity loss caused by safety effort, the income of the construction enterprise is $I - {k_E}''{k_E}'{S_E}^2/2 - {k_E}'{S_E}^2/2 = I - ({k_E}''{k_E}' + {k_E}'){S_E}^2/2$. Let $k_E = {k_E}''{k_E}' + {k_E}'$, and reassume the cost of the safety effort of the construction enterprise as $k_E {S_E}^2/2$.

Hypothesis 3. The level of construction safety is affected by the safety effort of the construction enterprise and construction workers. Under the influence of factors such as the aging of safety equipment, the level of construction safety will decline with time. The level of construction safety is a dynamic process with time. Referring to Nerlove arrow's goodwill dynamic equation [52] and other related research [53,54], the dynamic change process of the level of construction safety with time t is described as follows:

$$dS(t)/dt = \alpha S_E + \beta S_W - \delta S(t) \tag{5}$$

$S(t)$ is the level of construction safety at time t. α, β, and δ are shown in Table 1.

Hypothesis 4. Through the control test, Unto and Markku found that there is a significant linear relationship between the safety level and the accident rate, and the higher the safety level, the lower the accident rate [55]. Based on this research, the probability of accident is assumed as $P - \varepsilon S(t)$, where P, ε, and $S(t)$ are shown in Table 1. According to the solution of Equation (5) in the Appendix A, $S(t) = e^{-\delta t} S_0 + \frac{1-e^{-\delta t}}{\delta}(\alpha S_E + \beta S_W)$, where S_0 is the level of construction safety when $t = 0$. With the increase in t, $S(t)$ tends to $(\alpha S_E + \beta S_W)/\delta$. To ensure $P - \varepsilon S(t) \geq 0$, we assume $0 \leq \varepsilon < P\delta/(\alpha S_E + \beta S_W)$.

Hypothesis 5. The construction enterprise and construction workers have the same discount rate ρ, where $\rho > 0$. The discount rate refers to the interest rate used to change future payments into the present value. They both seek the degree of safety effort to maximize income in an infinite time region.

2.4. Model without Safety Incentive Mechanism

When there is no safety incentive mechanism, the salary paid by the construction enterprise to construction workers does not change with the change in construction workers' safety efforts. In $[0, \infty]$, the income functions of the construction enterprise and construction workers are:

$$\pi_E = \int_0^\infty e^{-\rho t}\{I - k_E {S_E}^2/2 - (P - \varepsilon S)L_E - W\}dt \tag{6}$$

$$\pi_W = \int_0^\infty e^{-\rho t}\{W - k_W {S_W}^2/2 - (P - \varepsilon S)L_W\}dt \tag{7}$$

where π_E is the income function of the construction enterprise. π_W is the income function of construction workers. $(P - \varepsilon S)L_E$ is the loss expectation of the construction enterprise when the accident occurs. $(P - \varepsilon S)L_W$ is the loss expectation of construction workers when the accident occurs. The decision-making problem faced by the construction enterprise and construction workers is to seek S_E and S_W to maximize π_E and π_W under the condition of $dS(t)/dt = \alpha S_E + \beta S_W - \delta S(t)$, where $S(0) = S_0 > 0$. By constructing Hamilton Jacobi Bellman equation (HJB), the Nash equilibrium solution of the model can be obtained. The calculation process is shown in the Appendix A. In the equilibrium state, the safety efforts of the construction enterprise and construction workers are:

$${S_E}^N = \frac{\varepsilon L_E \alpha}{(\rho + \delta)k_E} \tag{8}$$

$${S_W}^N = \frac{\varepsilon L_W \beta}{(\rho + \delta)k_W} \tag{9}$$

where ${S_E}^N$ is the safety effort of the construction enterprise. ${S_W}^N$ is the safety effort of construction workers. N refers to the situation without a safety incentive mechanism. The evolution process of the level of construction safety is:

$$S^N(t) = e^{-\delta t} S_0 + \frac{1 - e^{-\delta t}}{\delta(\rho + \delta)}[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\varepsilon L_W \beta^2}{k_W}] \tag{10}$$

In the equilibrium state, the income of the construction enterprise and the income of construction workers are:

$$V_E{}^N = \frac{\varepsilon L_E}{\rho+\delta} S^N(t) + \frac{I - W - PL_E}{\rho} + \frac{\varepsilon L_E}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E \alpha^2}{2k_E} + \frac{\varepsilon L_W \beta^2}{k_W}] \tag{11}$$

$$V_W{}^N = \frac{\varepsilon L_W}{\rho+\delta} S^N(t) + \frac{W - PL_W}{\rho} + \frac{\varepsilon L_W}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\varepsilon L_W \beta^2}{2k_W}] \tag{12}$$

where $V_E{}^N$ is the income of the construction enterprise. $V_W{}^N$ is the income of construction workers. The total income of the construction enterprise and construction workers is:

$$V_{EW}{}^N = V_E{}^N + V_W{}^N = \frac{\varepsilon L_E + \varepsilon L_W}{\rho+\delta} S^N(t) + \frac{I - PL_E - PL_W}{\rho} + \frac{1}{\rho(\rho+\delta)^2}[\frac{(\varepsilon^2 L_E{}^2 + 2\varepsilon L_W \varepsilon L_E)\alpha^2}{2k_E} + \frac{(\varepsilon^2 L_W{}^2 + 2\varepsilon L_E \varepsilon L_W)\beta^2}{2k_W}] \tag{13}$$

2.5. Model under the Reward and Punishment Mechanism

In the situation with the reward and punishment mechanism, it is assumed that the salary paid by the construction enterprise to construction workers is $W - (L - \mu S_W)$. L is the maximum punishment for construction workers. μ is the coefficient of reward and punishment, which indicates the impact of construction workers' safety effort on the reward and punishment. In $[0, \infty]$, the income functions of the construction enterprise and construction workers are:

$$\pi_E = \int_0^\infty e^{-\rho t}\{I - k_E S_E{}^2/2 - (P - \varepsilon S)L_E - [W - (L - \mu S_W)]\}dt \tag{14}$$

$$\pi_W = \int_0^\infty e^{-\rho t}\{[W - (L - \mu S_W)] - k_W S_W{}^2/2 - (P - \varepsilon S)L_W\}dt \tag{15}$$

where $dS(t)/dt = \alpha S_E + \beta S_W - \delta S(t)$. $S(0) = S_0 > 0$. The solving process of this model is similar to that of the model without an incentive mechanism. In the equilibrium state, the safety efforts of the construction enterprise and construction workers are:

$$S_E{}^R = \frac{\varepsilon L_E \alpha}{(\rho+\delta)k_E} \tag{16}$$

$$S_W{}^R = \frac{\mu(\rho+\delta) + \varepsilon L_W \beta}{(\rho+\delta)k_W} \tag{17}$$

where R represents the situation with the reward and punishment mechanism. The evolution process of the level of construction safety is:

$$S^R(t) = e^{-\delta t} S_0 + \frac{1 - e^{-\delta t}}{\delta(\rho+\delta)}[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\mu(\rho+\delta)\beta + \varepsilon L_W \beta^2}{k_W}] \tag{18}$$

In the equilibrium state, the income of the construction enterprise and the income of construction workers are:

$$V_E{}^R = \frac{\varepsilon L_E}{\rho+\delta} S^R(t) + \frac{I - PL_E - W + L}{\rho} - \frac{\varepsilon^2 L_E{}^2 \alpha^2}{2\rho(\rho+\delta)^2 k_E} - \frac{\mu^2(\rho+\delta) + \mu\varepsilon L_W \beta}{\rho(\rho+\delta)k_W} + \frac{\varepsilon L_E}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\mu\beta(\rho+\delta) + \varepsilon L_W \beta^2}{k_W}] \tag{19}$$

$$V_W{}^R = \frac{\varepsilon L_W}{\rho+\delta} S^R(t) + \frac{W - L - PL_W}{\rho} + \frac{\mu^2(\rho+\delta) + \mu\varepsilon L_W \beta}{\rho(\rho+\delta)k_W} - \frac{[\mu(\rho+\delta) + \varepsilon L_W \beta]^2}{2\rho(\rho+\delta)^2 k_W} + \frac{\varepsilon L_W}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\mu\beta(\rho+\delta) + \varepsilon L_W \beta^2}{k_W}] \tag{20}$$

The total income of the construction enterprise and construction workers is:

$$V_{EW}{}^R = V_E{}^R + V_W{}^R = \frac{\varepsilon L_E + \varepsilon L_W}{\rho+\delta} S^R(t) + \frac{I - PL_E - PL_W}{\rho} - \frac{\varepsilon^2 L_E{}^2 \alpha^2}{2\rho(\rho+\delta)^2 k_E} - \frac{[\mu(\rho+\delta) + \varepsilon L_W \beta]^2}{2\rho(\rho+\delta)^2 k_W} + \frac{\varepsilon L_E + \varepsilon L_W}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\mu\beta(\rho+\delta) + \varepsilon L_W \beta^2}{k_W}] \tag{21}$$

To further improve the level of construction safety, the following first designs a revenue sharing mechanism and then designs a combination mechanism composed of the safety reward and punishment mechanism and the income sharing mechanism.

2.6. Model under the Income Sharing Mechanism

In the situation with the income sharing mechanism, it is assumed that the construction enterprise and construction workers share the income through contract (d_E, d_W), where d_E is the proportion of income allocated to the construction enterprise. d_W is the proportion of income allocated to construction workers. $d_E + d_W = 1$. In $[0, \infty]$, the income functions of the construction enterprise and construction workers are:

$$\pi_E = \int_0^\infty e^{-\rho t}\{d_E[I - k_E {S_E}^2/2 - (P - \varepsilon S)L_E]\}dt \tag{22}$$

$$\pi_W = \int_0^\infty e^{-\rho t}\{d_W[I - k_E {S_E}^2/2 - (P - \varepsilon S)L_E] - k_W {S_W}^2/2 - (P - \varepsilon S)L_W\}dt \tag{23}$$

where $dS(t)/dt = \alpha S_E + \beta S_W - \delta S(t)$, $S(0) = S_0 > 0$. In the equilibrium state, the safety efforts of the construction enterprise and construction workers are:

$${S_E}^C = \frac{\varepsilon L_E \alpha}{(\rho + \delta)k_E} \tag{24}$$

$${S_W}^C = \frac{d_W \varepsilon L_E \beta + \varepsilon L_W \beta}{(\rho + \delta)k_W} \tag{25}$$

where C represents the situation with the income sharing contract. The evolution process of the level of construction safety is:

$$S^C(t) = e^{-\delta t}S_0 + \frac{1 - e^{-\delta t}}{\delta(\rho + \delta)}\left[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{(d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{k_W}\right] \tag{26}$$

In the equilibrium state, the income of the construction enterprise and the income of construction workers are:

$${V_E}^C = \frac{d_E \varepsilon L_E}{\rho + \delta}S^C(t) + \frac{d_E(I - PL_E)}{\rho} + \frac{d_E \varepsilon L_E}{\rho(\rho + \delta)^2}\left[\frac{\varepsilon L_E \alpha^2}{2k_E} + \frac{(d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{k_W}\right] \tag{27}$$

$${V_W}^C = \frac{d_W \varepsilon L_E + \varepsilon L_W}{\rho+\delta}S^C(t) + \frac{d_W(I - PL_E) - PL_W}{\rho} - \frac{d_W \varepsilon^2 {L_E}^2 \alpha^2}{2k_E\rho(\rho+\delta)^2} + \frac{(d_W \varepsilon L_E + \varepsilon L_W)}{\rho(\rho+\delta)^2}\left[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{(d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{2k_W}\right] \tag{28}$$

The total income of the construction enterprise and construction workers is:

$$\begin{aligned} V_{EW}^C = {} & \frac{\varepsilon L_E + \varepsilon L_W}{\rho+\delta}S^C(t) + \frac{I - PL_E - PL_W}{\rho} + \frac{d_E \varepsilon L_E}{\rho(\rho+\delta)^2}\left[\frac{\varepsilon L_E \alpha^2}{2k_E} + \frac{(d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{k_W}\right] - \\ & \frac{d_W \varepsilon^2 L_E^2 \alpha^2}{2k_E\rho(\rho+\delta)^2} + \frac{(d_W \varepsilon L_E + \varepsilon L_W)}{\rho(\rho+\delta)^2}\left[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{(d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{2k_W}\right] \end{aligned} \tag{29}$$

2.7. Model under the Combination Incentive Mechanism

Under the combination mechanism composed of the reward and punishment mechanism and the income sharing mechanism, the income functions of the construction enterprise and construction workers are:

$$\pi_E = \int_0^\infty e^{-\rho t}\{d_E[I - k_E {S_E}^2/2 - (P - \varepsilon S)L_E] + (L - \mu S_W)\}dt \tag{30}$$

$$\pi_W = \int_0^\infty e^{-\rho t}\{d_W[I - k_E {S_E}^2/2 - (P - \varepsilon S)L_E] - (L - \mu S_W) - k_W {S_W}^2/2 - (P - \varepsilon S)L_W\}dt \tag{31}$$

where $dS(t)/dt = \alpha S_E + \beta S_W - \delta S(t)$. $S(0) = S_0 > 0$. In the equilibrium state, the safety efforts of the construction enterprise and construction workers are:

$$S_E{}^{RC} = \frac{\varepsilon L_E \alpha}{(\rho+\delta)k_E} \tag{32}$$

$$S_w{}^{RC} = \frac{(\rho+\delta)\mu + d_W \varepsilon L_E \beta + \varepsilon L_W \beta}{(\rho+\delta)k_W} \tag{33}$$

where RC represents the situation with the joint action of the reward and punishment mechanism and the income sharing mechanism. The evolution process of the level of construction safety is:

$$S^{RC}(t) = e^{-\delta t}S_0 + \frac{1-e^{-\delta t}}{\delta(\rho+\delta)}\left[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{(\rho+\delta)\mu\beta + (d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{k_W}\right] \tag{34}$$

In the equilibrium state, the income of the construction enterprise and the income of construction workers are:

$$V_E{}^{RC} = \frac{d_E \varepsilon L_E}{\rho+\delta}S^{RC}(t) + \frac{d_E(I-PL_E)+L}{\rho} - \frac{d_E \varepsilon^2 L_E{}^2 \alpha^2}{2\rho(\rho+\delta)^2 k_E} - \frac{\mu^2(\rho+\delta)+\mu(d_W \varepsilon L_E + \varepsilon L_W)\beta}{\rho(\rho+\delta)k_W} + \frac{d_E \varepsilon L_E}{\rho(\rho+\delta)^2}\left[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\mu(\rho+\delta)\beta + (d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{k_W}\right] \tag{35}$$

$$\begin{aligned} V_W{}^{RC} = {} & \frac{d_W \varepsilon L_E + \varepsilon L_W}{\rho+\delta}S^{RC}(t) + \frac{d_W(I-PL_E)-L-PL_W}{\rho} + \frac{\mu^2(\rho+\delta)+\mu(d_W \varepsilon L_E + \varepsilon L_W)\beta}{\rho(\rho+\delta)k_W} - \\ & \frac{d_W \varepsilon^2 L_E^2 \alpha^2}{2\rho(\rho+\delta)^2 k_E} - \frac{[\mu(\rho+\delta)+(d_W \varepsilon L_E + \varepsilon L_W)\beta]^2}{2\rho(\rho+\delta)^2 k_W} + \frac{d_W \varepsilon L_E + \varepsilon L_W}{\rho(\rho+\delta)^2}\left[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\mu(\rho+\delta)\beta + (d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{k_W}\right] \end{aligned} \tag{36}$$

The total income of the construction enterprise and construction workers is:

$$V_{EW}{}^{RC} = \frac{\varepsilon L_E + \varepsilon L_W}{\rho+\delta}S^{RC}(t) + \frac{I-PL_E-PL_W}{\rho} - \frac{\varepsilon^2 L_E{}^2 \alpha^2}{2\rho(\rho+\delta)^2 k_E} - \frac{[\mu(\rho+\delta)+(d_W \varepsilon L_E + \varepsilon L_W)\beta]^2}{2\rho(\rho+\delta)^2 k_W} + \frac{\varepsilon L_E + \varepsilon L_W}{\rho(\rho+\delta)^2}\left[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\mu(\rho+\delta)\beta + (d_W \varepsilon L_E + \varepsilon L_W)\beta^2}{k_W}\right]. \tag{37}$$

3. Model Results Discussion

3.1. Comparison of Model Results under Different Mechanisms

It can be seen from $S_E{}^N = \frac{\varepsilon L_E \alpha}{(\rho+\delta)k_E}$, $S_W{}^N = \frac{\varepsilon L_W \beta}{(\rho+\delta)k_W}$, $S_E{}^R = \frac{\varepsilon L_E \alpha}{(\rho+\delta)k_E}$, $S_W{}^R = \frac{\mu(\rho+\delta)+\varepsilon L_W \beta}{(\rho+\delta)k_W}$, $S_E{}^C = \frac{\varepsilon L_E \alpha}{(\rho+\delta)k_E}$, $S_W{}^C = \frac{d_W \varepsilon L_E \beta + \varepsilon L_W \beta}{(\rho+\delta)k_W}$, $S_E{}^{RC} = \frac{\varepsilon L_E \alpha}{(\rho+\delta)k_E}$, and $S_w{}^{RC} = \frac{(\rho+\delta)\mu + d_W \varepsilon L_E \beta + \varepsilon L_W \beta}{(\rho+\delta)k_W}$ that the greater the accident loss L_E or L_W, the greater the safety effort of the construction enterprise or construction workers. The smaller the cost of safety effort k_E or k_W, the greater the safety effort of the construction enterprise or construction workers. Compared to the situation without an incentive mechanism, the safety reward and punishment mechanism will not affect the safety effort of the construction enterprise but will improve the safety effort of construction workers. In addition, the greater the coefficient of reward and punishment, the higher the safety effort of construction workers. Compared with the situation without an incentive mechanism, the income sharing mechanism will not affect the safety effort of the construction enterprise but will improve the safety effort of construction workers. Moreover, the greater the proportion of income allocated to construction workers, the higher the safety effort of construction workers. Compared with the situation with the safety reward and punishment mechanism and the situation with the income sharing mechanism, the safety effort of construction workers under the combination mechanism is higher. According to $S^N(t)$, $S^R(t)$, $S^C(t)$, and $S^{RC}(t)$, the following proposition can be obtained.

Proposition 1. *Compared with the situation without an incentive mechanism, both the safety reward and punishment mechanism and the income sharing mechanism can improve the level of construction safety. In addition, the level of construction safety under the combination incentive mechanism is higher.*

Proof of Proposition 1. $S^R(t) - S^N(t) = \frac{(1-e^{-\delta t})\mu(\rho+\delta)\beta}{\delta(\rho+\delta)k_W} > 0$, $S^C(t) - S^N(t) = \frac{(1-e^{-\delta t})d_W \varepsilon L_E \beta^2}{\delta(\rho+\delta)k_W} > 0$, $S^{RC}(t) - S^R(t) = \frac{(1-e^{-\delta t})d_W \varepsilon L_E \beta^2}{\delta(\rho+\delta)k_W} > 0$, $S^{RC}(t) - S^C(t) = \frac{(1-e^{-\delta t})(\rho+\delta)\mu\beta}{\delta(\rho+\delta)k_W} > 0$, where, $S^N(t)$, $S^R(t)$, $S^C(t)$, and $S^{RC}(t)$ represent the safety level without an incentive mechanism, the safety level under the reward and punishment mechanism, the safety level under the income sharing mechanism, and the safety level under the combination incentive mechanism, respectively. □

According to the income of the construction enterprise and the income of construction workers under different situations, the following proposition can be obtained.

Proposition 2. *Compared with the situation without an incentive mechanism, when* $\mu < \mu^* = \frac{2\rho(1-e^{-\delta t})(\varepsilon L_E + \varepsilon L_W)\beta + 2\delta\varepsilon L_E \beta}{\delta(\rho+\delta)}$*, the safety reward and punishment mechanism can improve the total income of the construction enterprise and construction workers. When* $L_1 < L < L_2$*, the reward and punishment mechanism can not only improve the income of construction workers but also improve the income of the construction enterprise, where* μ *dis the coefficient of reward and punishment, and* L *is the maximum punishment to construction workers.* $L_1 = \frac{\delta[\mu^2(\rho+\delta)+\mu\varepsilon L_W \beta]}{\delta(\rho+\delta)k_W} - \frac{\mu[\rho(1-e^{-\delta t})+\delta]\varepsilon L_E \beta}{\delta(\rho+\delta)k_W}$*, and* $L_2 = \frac{\mu[\rho(1-e^{-\delta t})+\delta]\varepsilon L_W \beta}{\delta(\rho+\delta)k_W} + \frac{\mu^2(\rho+\delta)^2 - \varepsilon^2 L_W{}^2 \beta^2}{2(\rho+\delta)^2 k_W}$.

Proof of Proposition 2. ${V_{EW}}^R - {V_{EW}}^N = \frac{(1-e^{-\delta t})\mu(\varepsilon L_E + \varepsilon L_W)\beta}{\delta(\rho+\delta)k_W} + \frac{\mu\varepsilon L_E \beta}{\rho(\rho+\delta)k_W} - \frac{\mu^2}{2\rho k_W}$. According to ${V_{EW}}^R > {V_{EW}}^N$, $\mu < \frac{2\rho(1-e^{-\delta t})(\varepsilon L_E + \varepsilon L_W)\beta + 2\delta\varepsilon L_E \beta}{\delta(\rho+\delta)}$. ${V_E}^R - {V_E}^N = \frac{\mu[\rho(1-e^{-\delta t})+\delta]\varepsilon L_E \beta}{\delta\rho(\rho+\delta)k_W} + \frac{L}{\rho} - \frac{\mu^2(\rho+\delta)+\mu\varepsilon L_W \beta}{\rho(\rho+\delta)k_W}$. According to ${V_E}^R > {V_E}^N$, $L > L_1$. ${V_W}^R - {V_W}^N = \frac{\mu[\rho(1-e^{-\delta t})+\delta]\varepsilon L_W \beta}{\delta\rho(\rho+\delta)k_W} + \frac{\mu^2(\rho+\delta)^2 - \varepsilon^2 L_W{}^2 \beta^2}{2\rho(\rho+\delta)^2 k_W} - \frac{L}{\rho}$. According to ${V_W}^R > {V_W}^N$, $L < L_2$, where L_1 and L_2 are shown in Proposition 2. □

According to Proposition 2, under certain conditions, the reward and punishment mechanism designed according to the effort of construction workers in construction safety can not only improve the safety level but also make the construction enterprise and construction workers mutually beneficial.

Proposition 3. *Compared with the situation without an incentive mechanism, the income sharing mechanism can improve the total income of the construction enterprise and construction workers. Under the condition of* $\frac{A_2 - \sqrt{A_2{}^2 - 4A_1 {V_E}^N}}{2A_1} < {d_E}^* < min\{\frac{A_2 + \sqrt{A_2{}^2 - 4A_1 {V_E}^N}}{2A_1}, 1 + \frac{A_4 - \sqrt{A_4{}^2 + 4A_3 W_1/\rho}}{2A_3}\}$ *or* $max\{\frac{A_2 - \sqrt{A_2{}^2 - 4A_1 {V_E}^N}}{2A_1}, 1 + \frac{A_4 + \sqrt{A_4{}^2 + 4A_3 W_1/\rho}}{2A_3}\} < {d_E}^* < \frac{A_2 + \sqrt{A_2{}^2 - 4A_1 {V_E}^N}}{2A_1}$*, the income sharing mechanism* $({d_E}^*, 1 - {d_E}^*)$ *can not only improve the income of construction workers but can also improve the income of the construction enterprise, where* ${d_E}^*$ *is the proportion of income obtained by the construction enterprise in the income sharing mechanism.* $A_1 = \frac{[(1-e^{-\delta t})\rho+\delta]\varepsilon^2 L_E{}^2 \beta^2}{\delta\rho(\rho+\delta)^2 k_W}$, $A_2 = {V_E}^N + W_1/\rho + A_1$, $A_3 = \frac{[2\rho(1-e^{-\delta t})+\delta]\varepsilon^2 L_E{}^2 \beta^2}{2\rho\delta(\rho+\delta)^2 k_W}$*, and* $A_4 = \frac{\varepsilon L_E e^{-\delta t} S_0}{\rho+\delta} + \frac{(I - PL_E)}{\rho} + \frac{[2\rho(1-e^{-\delta t})+\delta]\varepsilon^2 L_E{}^2 \alpha^2}{2\rho\delta(\rho+\delta)^2 k_E} + \frac{[2\rho(1-e^{-\delta t})+\delta]\varepsilon L_E \varepsilon L_W \beta^2}{\rho\delta(\rho+\delta)^2 k_W}$.

Proof of Proposition 3. ${V_{EW}}^C - {V_{EW}}^N = \frac{(1-e^{-\delta t})d_W(\varepsilon^2 L_E{}^2 + \varepsilon L_W \varepsilon L_E)\beta^2}{\delta(\rho+\delta)^2 k_W} + \frac{2d_W d_E \varepsilon^2 L_E{}^2 \beta^2 + 2d_E \varepsilon L_E \varepsilon L_W \beta^2 + d_W{}^2 \varepsilon^2 L_E{}^2 \beta^2}{2\rho(\rho+\delta)^2 k_W} > 0$. ${V_E}^C = -A_1 d_E{}^2 + A_2 d_E$. A_1 and A_2 are shown in Proposition 3. According to ${V_E}^C > {V_E}^N$, $\frac{A_2 - \sqrt{A_2{}^2 - 4A_1 {V_E}^N}}{2A_1} < d_E < \frac{A_2 + \sqrt{A_2{}^2 - 4A_1 {V_E}^N}}{2A_1}$. ${V_W}^C - {V_W}^N = A_3(1 - d_E)^2 + A_4(1 - d_E) - W_1/\rho$. According to ${V_W}^C > {V_W}^N$, $d_E < 1 + \frac{A_4 - \sqrt{A_4{}^2 + 4A_3 W_1/\rho}}{2A_3}$ or $d_E > 1 + \frac{A_4 + \sqrt{A_4{}^2 + 4A_3 W_1/\rho}}{2A_3}$. A_3 and A_4 are shown in Proposition

3. Thus, when $\frac{A_2-\sqrt{A_2{}^2-4A_1V_E{}^N}}{2A_1} < d_E{}^* < min\{\frac{A_2+\sqrt{A_2{}^2-4A_1V_E{}^N}}{2A_1}, 1+\frac{A_4-\sqrt{A_4{}^2+4A_3W_1/\rho}}{2A_3}\}$ or $max\{\frac{A_2-\sqrt{A_2{}^2-4A_1V_E{}^N}}{2A_1}, 1+\frac{A_4+\sqrt{A_4{}^2+4A_3W_1/\rho}}{2A_3}\} < d_E{}^* < \frac{A_2+\sqrt{A_2{}^2-4A_1V_E{}^N}}{2A_1}$, and $V_W{}^C > V_W{}^N$. □

According to Proposition 3, compared with the situation without incentive mechanism, the income sharing mechanism $(d_E{}^*, 1-d_E{}^*)$ can not only improve the safety level but also make the construction enterprise and construction workers mutually beneficial.

Proposition 4. *Compared with the reward and punishment mechanism, under the condition of* $d_E > \frac{2\mu(\rho+\delta)}{\varepsilon\beta L_E} - \frac{2\rho(1-e^{-\delta t})(L_E+L_W)}{\delta L_E} - 1$, *the combination mechanism composed of the reward and punishment mechanism and the income sharing mechanism can further improve the total income of the construction enterprise and construction workers. Under the condition of* $max\{\frac{B_1+B_2-\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}, \frac{2\mu(\rho+\delta)}{\varepsilon\beta L_E} - \frac{2\rho(1-e^{-\delta t})(L_E+L_W)}{\delta L_E} - 1\} < d_E{}^{**} < min\{\frac{B_1+B_2+\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}, 1+\frac{B_3-\sqrt{B_3{}^2+4B_4W_2/\rho}}{2B_4}\}$ *or* $max\{\frac{B_1+B_2-\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}, \frac{2\mu(\rho+\delta)}{\varepsilon\beta L_E} - \frac{2\rho(1-e^{-\delta t})(L_E+L_W)}{\delta L_E} - 1, 1+\frac{B_3+\sqrt{B_3{}^2+4B_4W_2/\rho}}{2B_4}\} < d_E{}^{**} < \frac{B_1+B_2+\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}$, *the combination mechanism can not only further improve the income of construction workers but can also further improve the income of the construction enterprise, where* d_E *is the proportion of income obtained by the construction enterprise and* $d_E{}^{**}$ *is the proportion in the income sharing mechanism.* $B_1 = \frac{[\rho(1-e^{-\delta t})+\delta]\varepsilon^2 L_E{}^2\beta^2}{\rho\delta(\rho+\delta)^2 k_W}$, $B_2 = \frac{[\rho\varepsilon L_E e^{-\delta t}S_0+(\rho+\delta)(I-PL_E)]}{\rho(\rho+\delta)} + \frac{[2\rho(1-e^{-\delta t})+\delta]\varepsilon^2 L_E{}^2\alpha^2}{2\rho\delta(\rho+\delta)^2 k_E} + \frac{[\rho(1-e^{-\delta t})+\delta]\mu\varepsilon L_E\beta}{\rho\delta(\rho+\delta)k_W} + \frac{[\rho(1-e^{-\delta t})+\delta]\varepsilon L_E\varepsilon L_W\beta^2}{\rho\delta(\rho+\delta)^2 k_W} + \frac{\mu\varepsilon L_E\beta}{\rho(\rho+\delta)k_W}$, $B_3 = \frac{\rho\varepsilon L_E e^{-\delta t}S_0+(\rho+\delta)(I-PL_E)}{\rho(\rho+\delta)} + \frac{[2\rho(1-e^{-\delta t})+\delta]\varepsilon^2 L_E{}^2\alpha^2}{2\rho\delta(\rho+\delta)^2 k_E} + \frac{[\rho(1-e^{-\delta t})+\delta]\mu\varepsilon L_E\beta}{\rho\delta(\rho+\delta)k_W} + \frac{[2\rho(1-e^{-\delta t})+\delta]\varepsilon L_E\varepsilon L_W\beta^2}{\rho\delta(\rho+\delta)^2 k_W}$, $B_4 = \frac{[2\rho(1-e^{-\delta t})+\delta]\varepsilon^2 L_E{}^2\beta^2}{2\rho\delta(\rho+\delta)^2 k_W}$.

Proof of Proposition 4. $V_{EW}{}^{RC} - V_{EW}{}^R = \frac{[2\rho(1-e^{-\delta t})+\delta(2-d_W)]d_W\varepsilon^2 L_E{}^2\beta^2+[2\rho(1-e^{-\delta t})\varepsilon L_W\beta-2\delta\mu(\rho+\delta)]d_W\varepsilon L_E\beta}{2\rho\delta(\rho+\delta)^2 k_W}$. When $d_E > \frac{2\mu(\rho+\delta)}{\varepsilon\beta L_E} - \frac{2\rho(1-e^{-\delta t})(L_E+L_W)}{\delta L_E} - 1$, $V_{EW}{}^{RC} > V_{EW}{}^R$. $V_E{}^{RC} - V_E{}^R = (1-d_E)d_E B_1 - (1-d_E)B_2 + \frac{W_2}{\rho}$. According to $V_E{}^{RC} > V_E{}^R$, $\frac{B_1+B_2-\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1} < d_E < \frac{B_1+B_2+\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}$. B_1 and B_2 are shown in Proposition 4. $V_W{}^{RC} - V_W{}^R = B_3 d_W + B_4 d_W{}^2 - \frac{W_2}{\rho}$. According to $V_W{}^{RC} > V_W{}^R$, $d_E < 1+\frac{B_3-\sqrt{B_3{}^2+4B_4W_2/\rho}}{2B_4}$ or $d_E > 1+\frac{B_3+\sqrt{B_3{}^2+4B_4W_2/\rho}}{2B_4}$. B_3 and B_4 are shown in Proposition 4. Thus, when $max\{\frac{B_1+B_2-\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}, \frac{2\mu(\rho+\delta)}{\varepsilon\beta L_E} - \frac{2\rho(1-e^{-\delta t})(L_E+L_W)}{\delta L_E} - 1\} < d_E{}^{**} < min\{\frac{B_1+B_2+\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}, 1+\frac{B_3-\sqrt{B_3{}^2+4B_4W_2/\rho}}{2B_4}\}$ or $max\{\frac{B_1+B_2-\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}, \frac{2\mu(\rho+\delta)}{\varepsilon\beta L_E} - \frac{2\rho(1-e^{-\delta t})(L_E+L_W)}{\delta L_E} - 1, 1+\frac{B_3+\sqrt{B_3{}^2+4B_4W_2/\rho}}{2B_4}\} < d_E{}^{**} < \frac{B_1+B_2+\sqrt{(B_1+B_2)^2-4B_1(B_2-W_2/\rho)}}{2B_1}$, $V_E{}^{RC} > V_E{}^R$. and $V_W{}^{RC} > V_W{}^R$. □

Proposition 5. *Compared with the income sharing mechanism, when* $\mu < \mu^{**} = \frac{2\rho(1-e^{-\delta t})(\varepsilon L_E+\varepsilon L_W)\beta+2d_E\delta\varepsilon L_E\beta}{\delta(\rho+\delta)}$, *the combination mechanism composed of the reward and punishment mechanism and the income sharing mechanism can further improve the total income of the construction enterprise and the construction workers. Under the condition of* $L_1{}' < L < L_2{}'$, *the combination mechanism can not only further improve the income of construction workers but can also further improve the income of the construction enterprise, where μ is the coefficient of the reward and punishment and L is the maximum punishment to construction workers.* $L_1{}' = \frac{\mu^2(\rho+\delta)+\mu\varepsilon L_E\beta+\mu\varepsilon L_W\beta}{(\rho+\delta)k_W} - \frac{\mu\rho\left(1-e^{-\delta t}\right)d_E\varepsilon L_E\beta}{\delta(\rho+\delta)k_W}$, $L_2{}' = \frac{\left[\left(1-e^{-\delta t}\right)\rho+\delta\right]\mu(d_W\varepsilon L_E+\varepsilon L_W)\beta}{\delta(\rho+\delta)k_W} + \frac{\mu^2}{2k_W}$.

Proof of Proposition 5. $V_{EW}{}^{RC} - V_{EW}{}^{C} = \frac{\mu\rho\left(1-e^{-\delta t}\right)(\varepsilon L_E+\varepsilon L_W)\beta+\mu d_E\delta\varepsilon L_E\beta}{\delta\rho(\rho+\delta)k_W} - \frac{\mu^2}{2\rho k_W}$. When $\mu < \mu^{**}$, $V_{EW}{}^{RC} > V_{EW}{}^{C}$. $V_E{}^{RC} - V_E{}^{C} = \frac{\mu\left(1-e^{-\delta t}\right)d_E\varepsilon L_E\beta}{\delta(\rho+\delta)k_W} + \frac{L}{\rho} - \frac{\mu^2(\rho+\delta)+\mu\varepsilon L_E\beta+\mu\varepsilon L_W\beta}{\rho(\rho+\delta)k_W}$. When $L > L_1{}'$, $V_E{}^{RC} > V_E{}^{C}$. $V_W{}^{RC} - V_W{}^{C} = \frac{\left[\left(1-e^{-\delta t}\right)\rho+\delta\right]\mu(d_W\varepsilon L_E+\varepsilon L_W)\beta}{\delta\rho(\rho+\delta)k_W} - \frac{L}{\rho} + \frac{\mu^2}{2\rho k_W}$. When $L < L_2{}'$, $V_W{}^{RC} > V_W{}^{C}$. μ^{**}, $L_1{}'$, and $L_2{}'$ are shown in Proposition 5. □

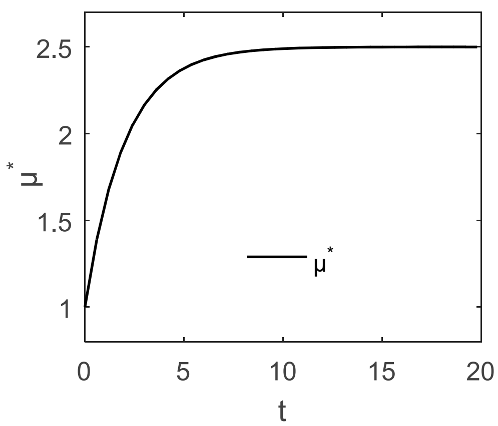
3.2. Numerical Example

3.2.1. Parameter Setting

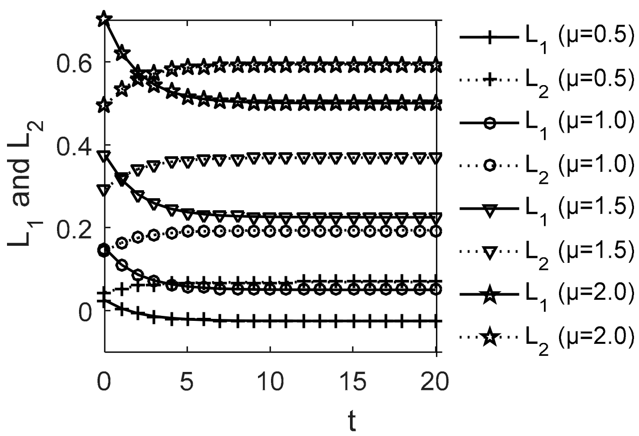
The following is an example of how to analyse the impact of incentive mechanisms on the model results. The values of each parameter are as follows: $I = 100$, $P = 0.01$, $\varepsilon = 0.001$, $L_E = 1000$, $L_W = 500$, $k_E = 10$, $k_W = 5$, $\alpha = 0.5$, $\beta = 0.5$, $\delta = 0.5$, $\rho = 0.5$, and $S_0 = 0.1$.

3.2.2. Influence of the Reward and Punishment Mechanism on Model Results

According to Proposition 2, compared with the situation without incentive mechanism, when the coefficient of reward and punishment satisfies $\mu < \mu^*$, the reward and punishment mechanism can improve the total income of the construction enterprise and construction workers. μ^* is shown in Figure 1a. When the maximum penalty L satisfies $L_1 < L < L_2$, the reward and punishment mechanism can improve the income of the construction enterprise and the income of construction workers at the same time. When μ is equal to 0.5, 1.0, 1.5, and 2, L_1 and L_2 are shown in Figure 1b.



(**a**)



(**b**)

Figure 1. The boundary of reward and punishment coefficient that can increase the total income and the boundary of the maximum penalty that can improve the income of the construction enterprise and the income of construction workers at the same time. (**a**) The boundary of reward and punishment coefficient, where μ^* is the upper boundary. (**b**) The boundary of the maximum penalty, where L_1 is the lower boundary and L_2 is the upper boundary.

When the maximum punishment L = 0.15 and the coefficient of reward and punishment takes different values, the level of construction safety is shown in Figure 2a. The total income of the construction enterprise and construction workers is shown in Figure 2b. The income of the construction enterprise is shown in Figure 2c. The income of construction workers is shown in Figure 2d, where μ and L satisfy $\mu < \mu^*$ and $L_1 < L < L_2$, respectively.

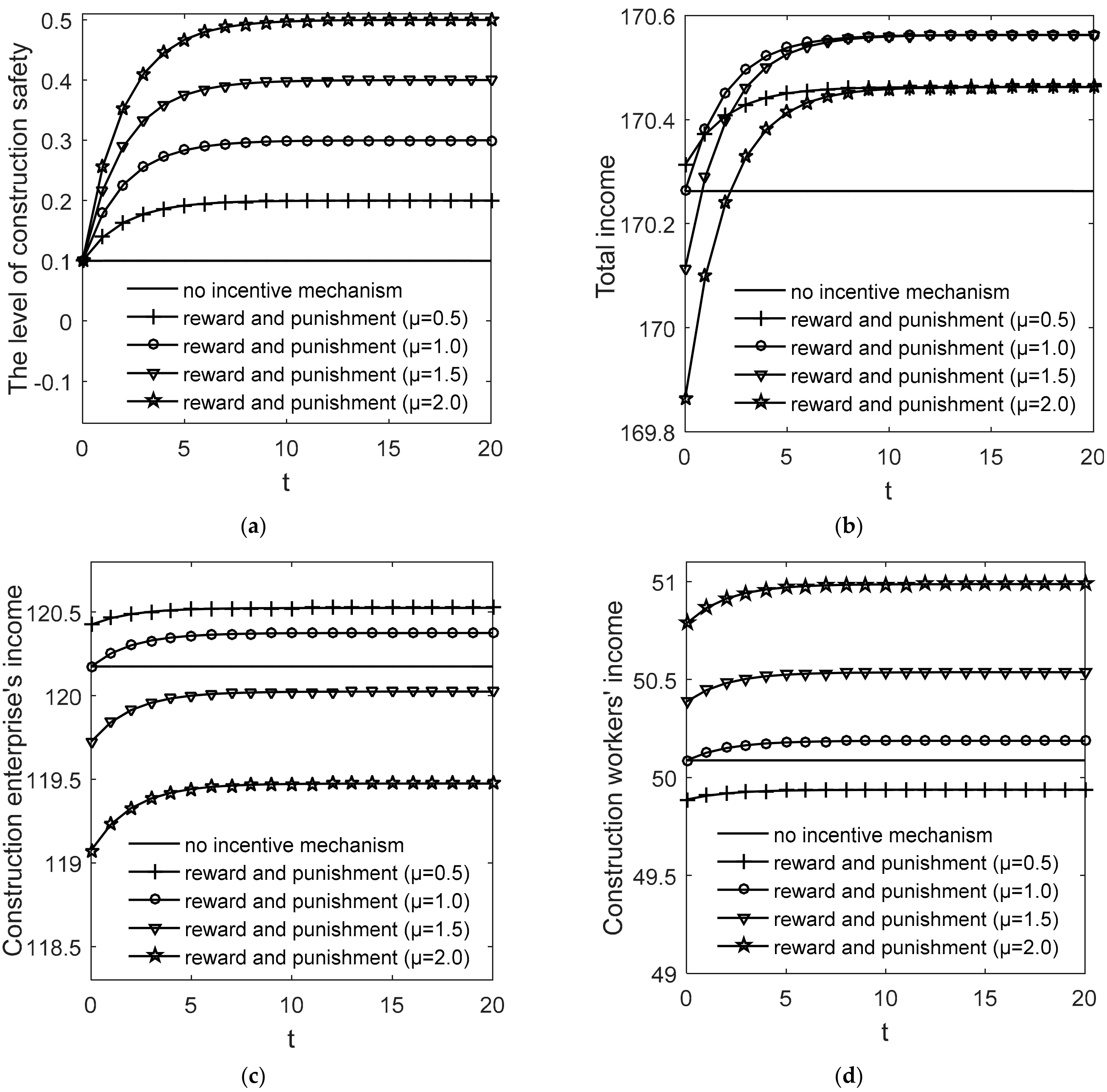


Figure 2. Influence of the reward and punishment mechanism on model results (where $L = 0.15$): (**a**) The level of construction safety; (**b**) Total income of the construction enterprise and construction workers; (**c**) Construction enterprise's income; (**d**) Construction workers' income.

It can be seen from Figure 2 that the safety reward and punishment mechanism can improve the level of construction safety. In addition, the greater the coefficient of reward and punishment, the higher the level of construction safety. However, a large coefficient of reward and punishment will make the income of the construction enterprise lower than that without an incentive mechanism. A small coefficient of reward and punishment will make construction workers' income lower than that without the incentive mechanism. The reward and punishment mechanism, which satisfies $\mu < \mu^*$ and $L_1 < L < L_2$, can not only improve the income of the construction enterprise but can also improve the income of construction workers. For example, $\mu = 1.0$ and $L = 0.15$ as shown in Figure 2.

3.2.3. Influence of Income Sharing Mechanism on Model Results

The impact of d_E on the level of construction safety is shown in Figure 3. d_E is the proportion of income allocated to the construction enterprise. As can be seen from Figure 3, the income sharing mechanism can improve the level of construction safety, and the smaller the value of d_E, the higher the level of construction safety.

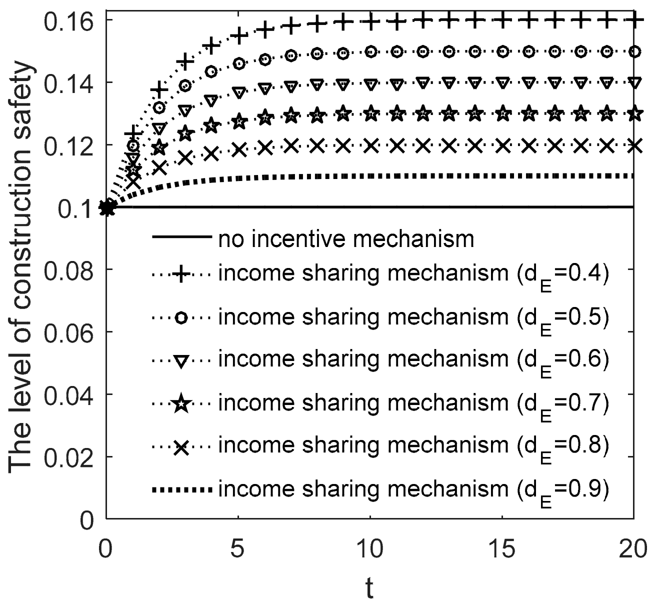


Figure 3. The impact of d_E on the level of construction safety.

According to Proposition 3, compared with the situation without incentive mechanism, the income sharing mechanism $(d_E{}^*, 1 - d_E{}^*)$ can make the construction enterprise and construction workers mutually beneficial. The value range of $d_E{}^*$ is shown in Figure 4.

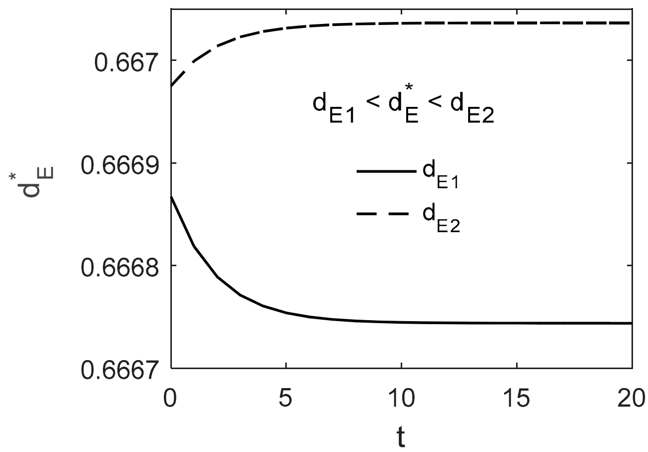


Figure 4. The income sharing mechanism that can make the construction enterprise and construction workers mutually beneficial.

According to $d_E{}^*$, when d_E is equal to 0.6660, 0.6665, 0.6670, and 0.6675, respectively, the income of the construction enterprise and the income of construction workers are shown in Figure 5.

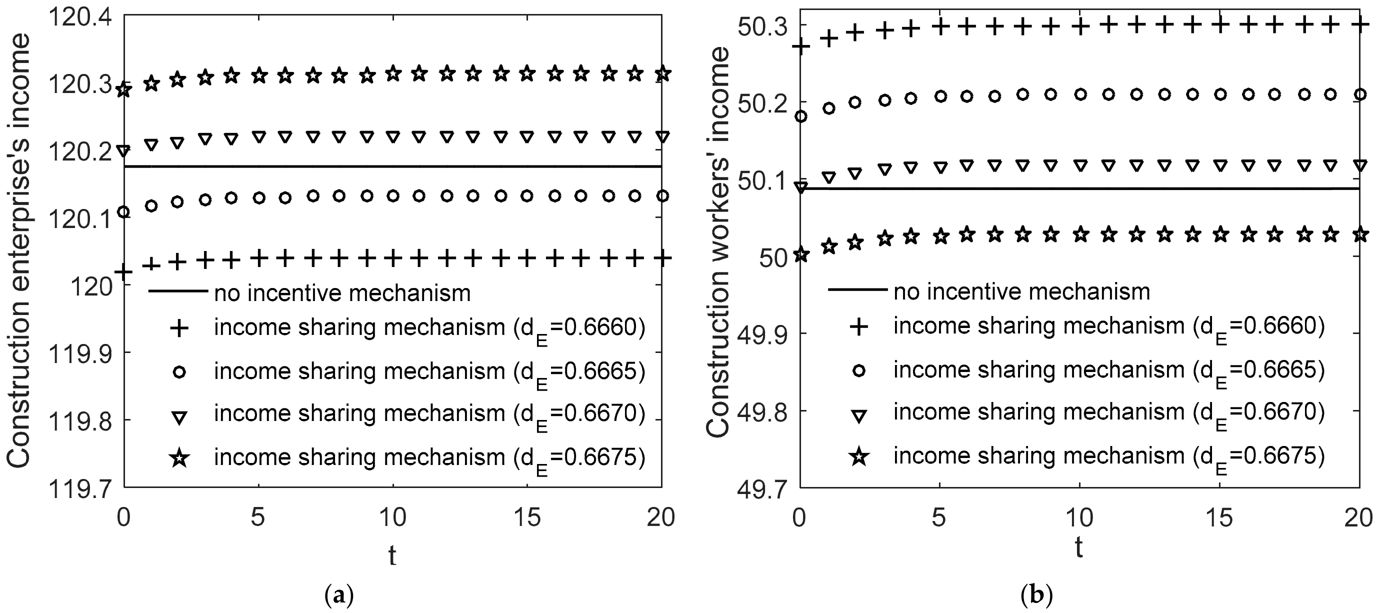


Figure 5. Influence of d_E on the income of the construction enterprise and construction workers: (**a**) Construction enterprise's income; (**b**) Construction workers' income.

As can be seen from Figure 5, a d_E with a larger value will make construction workers' income lower than that without the incentive mechanism. A d_E with smaller value will make the income of the construction enterprise lower than that without incentive mechanism. When the value of d_E is appropriate, it can improve construction workers' income and enterprise's income at the same time. For example, $d_E = 0.6670$ as shown in Figure 6.

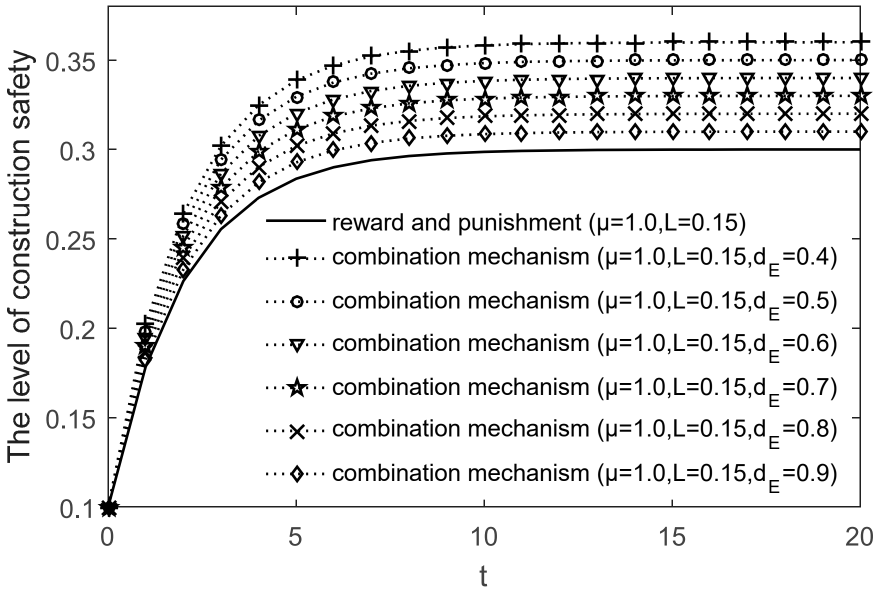


Figure 6. The level of construction safety under the combination mechanism when d_E takes different values.

3.2.4. Influence of Combination Mechanism on Model Results

When $\mu = 1.0$, $L = 0.15$, and d_E takes different values, the level of construction safety is shown in Figure 6. As can be seen from Figure 6, compared with the safety reward and punishment mechanism, the level of construction safety under the combination mechanism is higher.

According to Proposition 4, compared with the situation under the safety reward and punishment mechanism, $d_E{}^{**}$ can make the construction enterprise and construction workers mutually beneficial under the combination mechanism. When $\mu = 1.0$ and $L = 0.15$, the value range of $d_E{}^{**}$ is shown in Figure 7, where, μ and L satisfy $\mu < \mu^*$ and $L_1 < L < L_2$, respectively.

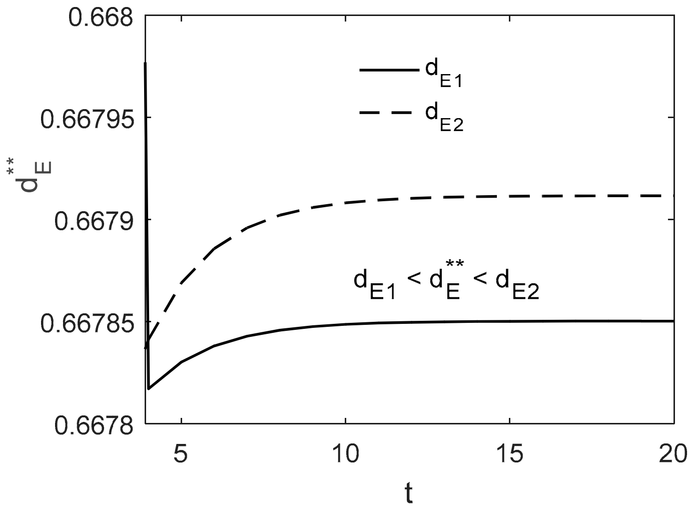


Figure 7. $d_E{}^{**}$ that can make the construction enterprise and construction workers mutually beneficial under the combination mechanism.

According to $d_E{}^{**}$, when d_E is equal to 0.6678, 0.6679, 0.6680, and 0.6681, the income of the construction enterprise and the income of construction workers are shown in Figures 8 and 9. It can be seen from Figures 8 and 9 that when d_E is large, the income of the construction enterprise under the combination mechanism is higher than that under the reward and punishment mechanism. When d_E is small, the construction workers' income under the combination mechanism is higher than that under the reward and punishment mechanism.

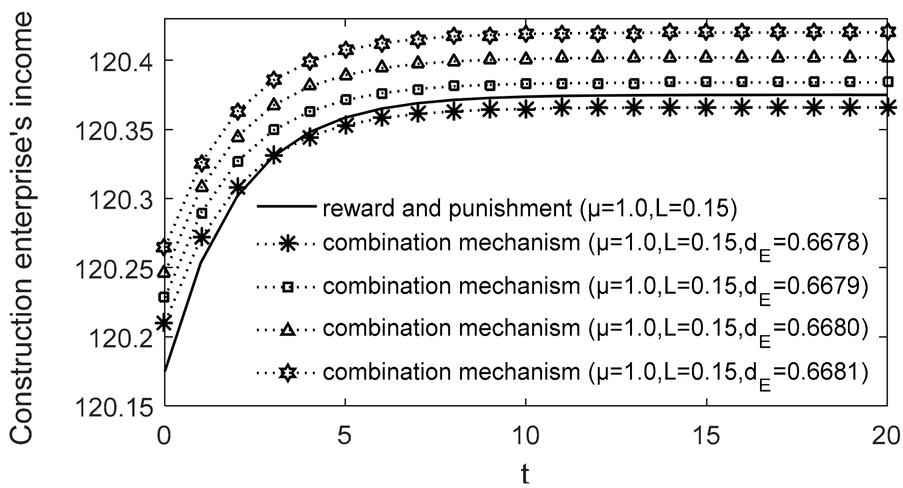


Figure 8. Construction enterprise's income when d_E takes different values under the combination mechanism.

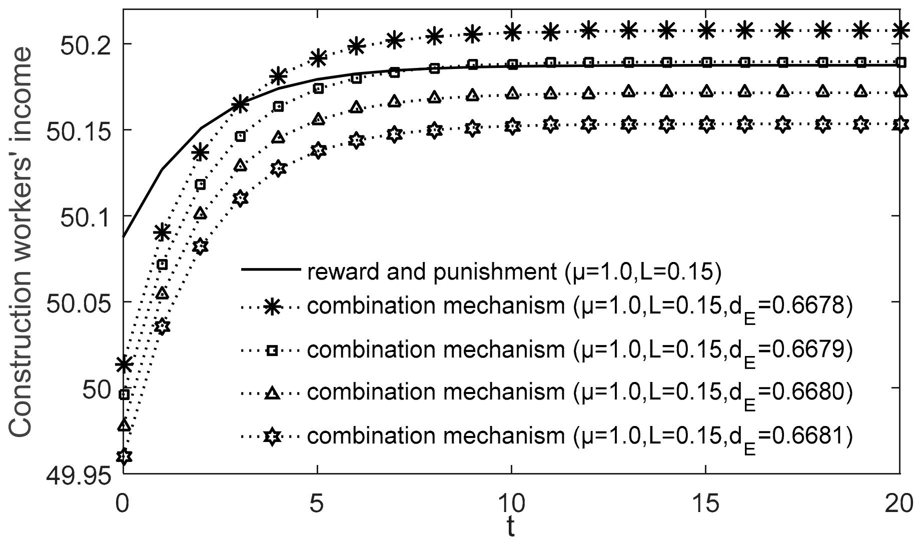


Figure 9. Construction workers' income when d_E takes different values under the combination mechanism.

When $d_E = 0.6670$, $L = 0.17$, and μ takes different values, the level of construction safety under the combination mechanism is shown in Figure 10. The income of the construction enterprise and the income of construction workers are shown in Figures 11 and 12. $d_E = 0.6670$ is the income sharing proportion that can make the construction enterprise and construction workers mutually beneficial under the income sharing mechanism.

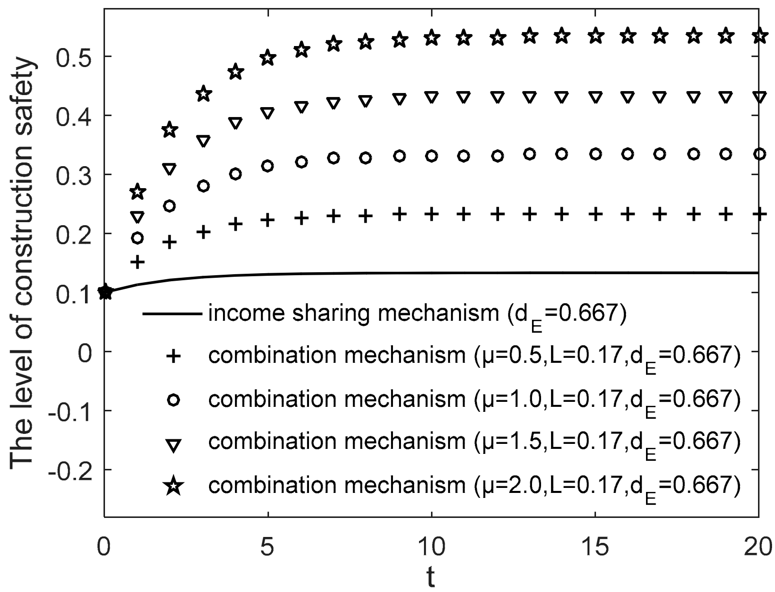


Figure 10. The level of construction safety when μ takes different values under the combination mechanism.

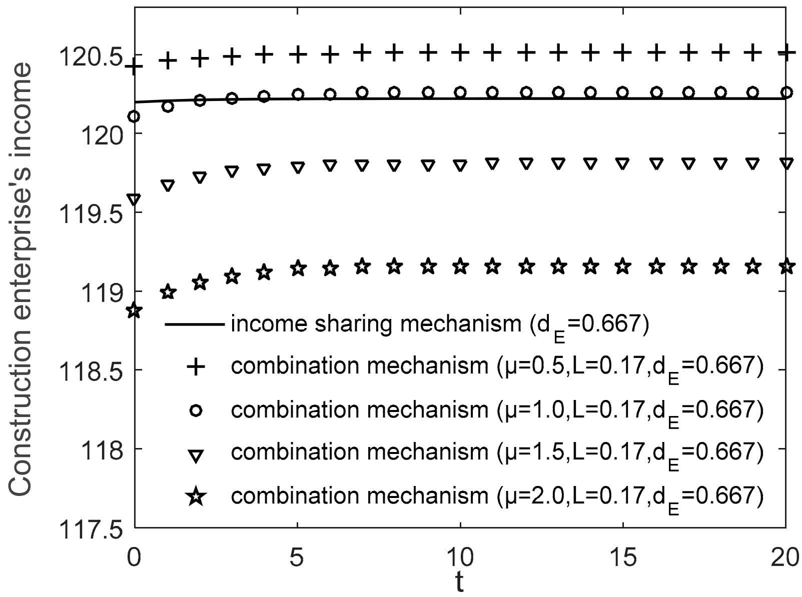


Figure 11. Construction enterprise's income when μ takes different values under the combination mechanism.

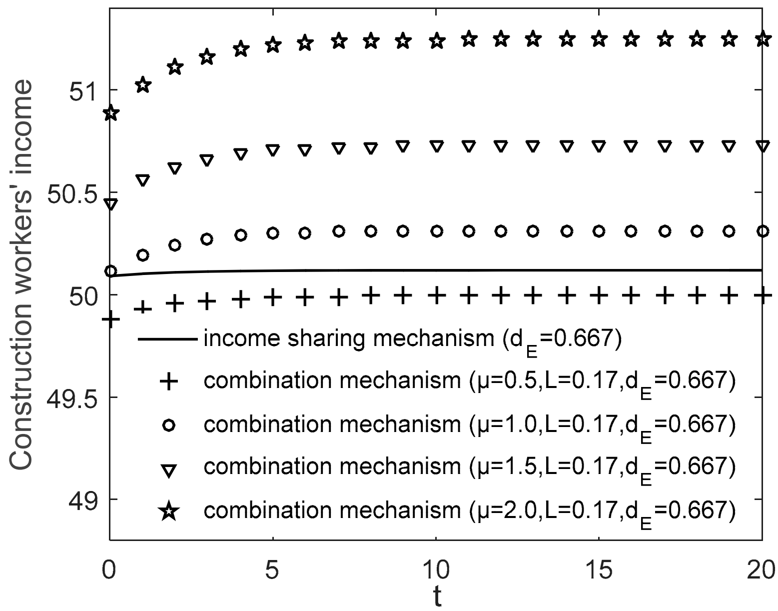


Figure 12. Construction workers' income when μ takes different values under the combination mechanism.

It can be seen from Figures 11 and 12 that when μ is small, the income of the construction enterprise under the combination mechanism is higher than that under the income sharing mechanism. When μ is large, construction workers' income under the combination mechanism is higher than that under the income sharing mechanism.

4. Conclusions and Suggestions

To improve the level of construction safety and make the construction enterprise and construction workers mutually beneficial, differential game models under different safety incentive mechanisms are established. In addition, the safety efforts and the income of the construction enterprise and construction workers under different mechanisms are compared.

The following conclusions are obtained through the research. (1) The safety efforts of the construction enterprise and construction workers increase with the increase in accident loss and the decrease in safety effort cost. (2) Compared with the situation without an incentive mechanism, the safety reward and punishment mechanism designed according to the safety effort of construction workers will not affect the safety effort of the construction enterprise but will improve the safety effort of construction workers. (3) Compared with the situation without an incentive mechanism, the income sharing mechanism will not affect the safety effort of the construction enterprise but will improve the safety effort of construction workers. (4) Compared with the situation without an incentive mechanism, the safety level under the safety reward and punishment mechanism is higher. In addition, the greater the impact of construction workers' safety efforts on safety rewards and punishment, the higher the level of construction safety. (5) Compared with the situation without incentive mechanism, the level of construction safety under the income sharing mechanism is higher, and the smaller the proportion of income allocated to the construction enterprise, the higher the level of construction safety. (6) The reward and punishment mechanism can make the construction enterprise and construction workers mutually beneficial. However, a larger coefficient of reward and punishment is not conducive to the improvement in the income of the construction enterprise. A smaller coefficient of reward and punishment is not conducive to the improvement in construction workers' income. (7) The income sharing mechanism can make the construction enterprise and construction workers mutually beneficial. However, when the proportion of income allocated to the construction enterprise is large, it is not conducive to the improvement in the income of construction workers. When the proportion of income allocated to the construction enterprise is small, it is not conducive to the improvement in the income of the construction enterprise. (8) The level of construction safety under the combination mechanism composed of the reward and punishment mechanism and the income sharing mechanism is higher than that under a single mechanism. (9) Under certain conditions, the income of the construction enterprise and the income of construction workers under the combination mechanism are higher than those under a single mechanism.

According to the above conclusions, the safety reward and punishment mechanism and income sharing mechanism that make construction enterprises and construction workers mutually beneficial can not only improve the level of construction safety but can also improve the income of construction enterprises and construction workers at the same time. The increase in income will reduce the conflict between construction enterprises and construction workers. The reduction in conflict will make the system of construction safety have lower accidents and higher efficiency.

Based on the above findings, the following suggestions are put forward for construction enterprises. (1) Construction enterprises can design a reward and punishment mechanism related to construction workers' safety efforts, and they can improve the safety level and income by adjusting the maximum punishment and the impact of construction workers' safety efforts on safety reward and punishment. (2) Construction enterprises and construction workers can sign an income sharing contract, and they can improve the safety level and income by adjusting the proportion of income distribution between construction enterprises and construction workers. (3) Construction enterprises can implement a safety incentive mechanism combining reward and punishment with income sharing.

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Appendix A

Model solving process without incentive mechanism.

The income functions of the construction enterprise and construction workers are as follows:

$$\pi_E = \int_0^{\infty} e^{-\rho t}\{I - k_E {S_E}^2/2 - (P - \varepsilon S)L_E - W\}dt$$

$$\pi_W = \int_0^{\infty} e^{-\rho t}\{W - k_W {S_W}^2/2 - (P - \varepsilon S)L_W\}dt$$

For any state $S \geq 0$, there are continuous differentiable functions $V_E(S)$ and $V_W(S)$ which satisfy the Hamilton Jacobi Bellman (HJB) equation:

$$\rho V_E(S) = \max_{S_E} \{I - k_E {S_E}^2/2 - (P - \varepsilon S)L_E - W_1 + V_E'(S)(\alpha S_E + \beta S_W - \delta S)\}$$

$$\rho V_W(S) = \max_{S_W} \{W_1 - k_W {S_W}^2/2 - (P - \varepsilon S)L_W + V_W'(S)(\alpha S_E + \beta S_W - \delta S)\}$$

Maximize the right end of the equation to obtain: $S_E = V_E'\alpha/k_E$, $S_W = V_W'\beta/k_W$. Substitute them into HJB equation to obtain:

$$\rho V_E = \left(\varepsilon L_E - V_E'\delta\right)S + I - {V_E'}^2\alpha^2/(2k_E) - PL_E - W_1 + V_E'[V_E'\alpha^2/k_E + V_W'\beta^2/k_W]$$

$$\rho V_W = \left(\varepsilon L_W - V_W'\delta\right)S + W_1 - \frac{{V_W'}^2\beta^2}{2k_W} - PL_W + V_W'[\frac{V_E'\alpha^2}{k_E} + \frac{V_W'\beta^2}{k_W}]$$

From the above formula, the linear function of S is the solution of HJB equation. Let $V_E(S) = e_1 S + e_2$, $V_W(S) = g_1 S + g_2$, where e_1, e_2, g_1, and g_2 are constants. Substitute them into HJB equation to obtain:

$$\rho e_1 S + \rho e_2 = (\varepsilon L_E - e_1\delta)S + I - \frac{{e_1}^2\alpha^2}{2k_E} - PL_E - W_1 + e_1[\frac{e_1\alpha^2}{k_E} + \frac{g_1\beta^2}{k_W}]$$

$$\rho g_1 S + \rho g_2 = (\varepsilon L_W - g_1\delta)S + W_1 - \frac{{g_1}^2\beta^2}{2k_W} - PL_W + g_1[\frac{e_1\alpha^2}{k_E} + \frac{g_1\beta^2}{k_W}]$$

where $e_1 = \frac{\varepsilon L_E}{\rho+\delta}$, $g_1 = \frac{\varepsilon L_W}{\rho+\delta}$, $e_2 = \frac{I-W_1-PL_E}{\rho} + \frac{\varepsilon L_E}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E\alpha^2}{2k_E} + \frac{\varepsilon L_W\beta^2}{k_W}]$, $g_2 = \frac{W_1-PL_W}{\rho} + \frac{\varepsilon L_W}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E\alpha^2}{k_E} + \frac{\varepsilon L_W\beta^2}{2k_W}]$. Substitute them into $V_E(S)$ and $V_W(S)$ to obtain:

$${V_E}^N = \frac{\varepsilon L_E}{\rho+\delta}S^N(t) + \frac{I - W_1 - PL_E}{\rho} + \frac{\varepsilon L_E}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E\alpha^2}{2k_E} + \frac{\varepsilon L_W\beta^2}{k_W}]$$

$${V_W}^N = \frac{\varepsilon L_W}{\rho+\delta}S^N(t) + \frac{W_1 - PL_W}{\rho} + \frac{\varepsilon L_W}{\rho(\rho+\delta)^2}[\frac{\varepsilon L_E\alpha^2}{k_E} + \frac{\varepsilon L_W\beta^2}{2k_W}]$$

Substitute ${V_E}^{N'} = \frac{\varepsilon L_E}{\rho+\delta}$ and ${V_W}^{N'} = \frac{\varepsilon L_W}{\rho+\delta}$ into $S_E = \frac{V_E'\alpha}{k_E}$ and $S_W = \frac{V_W'\beta}{k_W}$ to obtain:

$${S_E}^N = \frac{\varepsilon L_E\alpha}{(\rho+\delta)k_E}$$

$${S_W}^N = \frac{\varepsilon L_W\beta}{(\rho+\delta)k_W}$$

The general solution of $\dot{S}(t) = \alpha {S_W}^N + \beta {S_W}^N - \delta S$ is:

$$S(t) = e^{-\int \delta dt}[C + \int \left(\alpha {S_E}^F + \beta {S_W}^F\right) e^{\int \delta dt}]dt$$

When $t = 0$, $S(0) = S_0$. Based on this, we can obtain $C = S_0 - \left(\alpha {S_E}^F + \beta {S_W}^F\right)/\delta$. Substitute to $S(t)$ to obtain:

$$S^N(t) = e^{-\delta t} S_0 + \frac{1 - e^{-\delta t}}{\delta(\rho + \delta)}[\frac{\varepsilon L_E \alpha^2}{k_E} + \frac{\varepsilon L_W \beta^2}{k_W}]$$

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