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Research on Cooperative Innovation Strategy of Multi-Agent Enterprises Considering Knowledge Innovation and Environmental Social Responsibility

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ABSTRACT Based on the context of enterprise green innovation ecosystem, this paper discusses the decision-making of knowledge innovation and environmental social responsibility in the multi-agent enterprise R&D innovation system that is composed of core enterprises and satellite enterprises, and it provides a new perspective for comprehensively improving enterprise innovation ability. By using differential game method and considering the joint influence of knowledge innovation and environmental social responsibility, this paper analyzes the cooperative innovation of multi-agent enterprises under a dynamic framework and discusses the decision-making process and optimal returns of core enterprises and satellite enterprises under centralized decision, decentralized decision and Stackelberg master-slave game modes. The conclusions are as follows: (1) When multi-entity enterprise R&D and innovation system moderately fulfill their environmental social responsibilities, their income increases significantly, and the green innovation capability of green innovation ecosystem is enhanced effectively; (2) When the profit ratio of core enterprises is controlled above 1/3, and the subsidy rate of government on satellite enterprises is controlled below 2/3, the green innovation ecosystem is in a balanced state, and the innovation initiative of multi-agent enterprises reaches a high level; (3) Under centralized decision making, the revenue proportion of core enterprises decreases, but the overall revenue of R&D innovation system reaches the Pareto optimum. Finally, the differential game decision-making process is analyzed with an example to verify the validity of the model conclusion, which provides a scientific basis for the knowledge innovation decision of multi-agent enterprise R&D innovation system in the green innovation ecosystem and accelerates the process of carbon neutrality.

INDEX TERMS Carbon neutral, green innovation ecosystem, knowledge innovation, environmental social responsibility, differential game.

I. INTRODUCTION

''Carbon peak and carbon neutral'' has become a major development strategy for most countries around the world. According to the Intergovernmental Panel on Climate Change, the world must become carbon neutral by 2050 to meet the Paris agreement's 1.5°C temperature target [1]. At present, 137 countries have proposed specific targets to achieve carbon neutrality. Among them, Sweden proposed to become carbon neutral by 2045, while others such as the European Union, the United States and the United Kingdom proposed to become carbon neutral by 2050 [2]. Under the ''dual carbon'' strategic goal, the new mission for enterprises is to take the initiative for undertaking green technology innovation and environmental social responsibility, and the key approach to promote high-quality development of enterprises is to realize the synergistic coupling of the two. The essence of innovation is knowledge innovation, and knowledge innovation is a dynamic development process of knowledge acquisition, storage and sharing [3]. From the perspective of enterprise innovation ecosystem, all main enterprises actively participate in innovation interaction and

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create common value beyond their individual values [4], and the form of innovation is changing from individual innovation to network collaborative innovation [5].

Most of the world's industry leaders, such as Apple, IBM, Google, Microsoft, BYD, BOE, GREE, *et al.*, are early or in the process of establishing enterprise innovation ecosystems with themselves as the core. These ecosystems help core enterprises to complete knowledge acquisition and knowledge storage, and share knowledge with other members, thus improving the efficiency of knowledge innovation research and development of the ecosystem and creating a good effect of environmental social responsibility. Some large European and American companies took the lead in the wave of social responsibility movement. They not only demanded the implementation of social responsibility standards internally, but also required suppliers and exporters to assume social responsibility. Enterprises such as Avon, Bestbuy, McDonalds, and New Balance have made it clear that they will terminate their relationships with suppliers that fail to fulfill their social responsibilities. Meanwhile, the multi-core main body green innovation ecosystem jointly constructed by core enterprises and satellite enterprises, such as the innovation ecosystem in the field of new energy enterprises established by Chongqing Changan Automobile Company Limited, Chongqing Changan New Energy Automobile Co., LTD, Tsinghua University and other colleges and universities has better promoted the development of new energy vehicles and promoted the construction of a green ecological environment [6].

With the rapid increase of enterprise economic benefits, environmental problems have become increasingly prominent, and the environmental social responsibilities undertaken by enterprises are particularly significant, which directly affect the social image, value enhancement and sustainable development of enterprises [7]. As enterprises face increasing pressure from environmental protection, the status of ecological innovation in enterprise strategy is constantly improved [8], but the input of knowledge innovation directly increases the cost of enterprises, leading to the weakening of enterprise enthusiasm, and even may ignore the environmental effect in production activities [9]. In this case, the subsidies and incentive measures formulated by the government constitute the guidance and support of the innovation ecosystem and play a key role in enterprise knowledge innovation and green environmental social responsibility. The heterogeneity of enterprises' knowledge innovation is an important reason for the difference in industry competitiveness. Enterprises that improve their knowledge innovation level by fulfilling environmental social responsibility may be more likely to gain competitive advantages. In addition, the process of carbon neutrality provides a good opportunity for enterprises to fulfill their environmental social responsibilities and improve the level of knowledge innovation. There is a balanced relationship between knowledge innovation and environmental social responsibility. If an enterprise overperforms its environmental social responsibility or ignores its environmental social responsibility, its balanced relationship will be broken, which will have a serious negative impact on the sustainable development of the enterprise. Then, from the perspective of the innovation ecosystem, what are the decision-making situations of knowledge innovation and environmental social responsibility in the multi-agent R&D innovation system that is composed of core enterprises and satellite enterprises? What is the overall optimal revenue of multi-agent enterprise R&D innovation system and what is the optimal revenue of enterprise under different decision-making conditions? What are the effects on the optimal returns of core enterprises and satellite enterprises after the introduction of government subsidies for knowledge innovation and incentives for environmental effects? Is the centralized decision the optimal choice? All these questions are worth considering.

II. THEORETICAL BASIS AND RESEARCH FRAMEWORK

A. RESEARCH ON ENTERPRISE INNOVATION IN INNOVATION ECOSYSTEM

1) THE ROLE OF ENTERPRISES IN THE INNOVATION ECOSYSTEM

Combining the characteristics of green innovation and innovation ecosystem, green innovation ecosystem aims at improving green innovation ability and promoting the emergence of green innovation. It is a complex system of symbiotic competition and dynamic evolution formed between innovation subjects and innovation environment through the flow connection of knowledge and other elements [10]. The theory of core competence emphasizes that the development of enterprises needs the support of core technical competence, so a series of R&D and innovation activities are needed. The resource-based theory points out that enterprises maintain sustainable development through the acquisition and rational use of specific resources [11]. The enterprises in the innovation ecosystem are always committed to technological innovation and continue to maintain the absolute dominance of product innovation [12]. Nambisan and Sawhney proposed that the core enterprise in the ecosystem is the enterprise occupying the core position of the system strategy and resources, and usually plays a leading and decision-making role in the system, with the goal of coordinating development with other enterprises [13]. Anne believed that core enterprises are also the guides of the innovation ecosystem, leading enterprises in the ecosystem to carry out collaborative R&D and innovation of core technologies [14]. Clarysse *et al.* studied that core enterprises will also coordinate and guide members' technological research and development and social responsibility to achieve governance for the healthy development of the ecosystem [15]. Zhang *et al.* proposed that an innovation ecosystem centered on non-core enterprises with independent organizational structure embedded in modules can also become an important channel for knowledge and technology sharing [16]. Adner believed that good coordination and adaptation between the enterprise and other members is the key to the healthy development of the ecosystem [17]. Jacobides *et al.* further proposed that the main enterprise adjusts its position according to the ecosystem strategy and constantly adjusts with the evolution of the ecosystem [18].

2) SYMBIOTIC EVOLUTION AND GAME RELATIONSHIP BETWEEN THE ENTERPRISES AND OTHER SUBJECTS

According to the symbiotic evolution theory, only by establishing a sustainable relationship of complementary resources with other species can a species maintain a good ecological niche and promote the development of the community to a better situation [19]. Game theory studies the correlation between more than two subjects participating in decision-making. When the decision-making of any party is not independent of the strategies of other subjects, the decision-making and equilibrium process of the participants are analyzed [20]. Under the premise of symbiosis and win-win cooperation, the enterprises cannot create the optimal income alone, but they share complementary technologies, cutting-edge information and core capabilities with each other to improve the technical level through R&D and innovation, and then realize Pareto optimization. Hung and Chou emphasized that the main enterprises and other subjects, as different stakeholders, realize risk sharing and benefit sharing through the innovation ecosystem, thus they realize the non-zero-sum game of win-win cooperation [21]. Adner and Kapoor took nine technological changes in the global semiconductor industry as the research background, analyzed and showed that the co-competition and symbiosis relationship between enterprises has a positive impact on the vitality of the ecosystem, and pointed out that the ecological niche of the enterprises is interdependent with the external environment [22]. Yang and Li believed that resource sharing among the main bodies in the ecosystem can form a synergistic effect of the innovation system through optimal allocation of resources and effective division of labor, so as to enhance overall income and form core competitiveness [23]. Gawer and Cusumano concluded that core enterprises have a competitive game relationship with upstream and downstream enterprises or competitors in the same industry, so the position of dominant enterprises is easy to be replaced [24]. Mantovani *et al.* further analyzed the joint R&D innovation system constructed by the core enterprises and upstream and downstream enterprises, which will form a new competitive equilibrium state when facing challenges from competitors [25].

3) RESEARCH ON COLLABORATIVE INNOVATION BETWEEN CORE ENTERPRISES AND SATELLITE ENTERPRISES

Core enterprises usually refer to the leading enterprises with good development scale based on resource endowment, grasping cutting-edge information, and satellite enterprises refer to the enterprises that the core enterprises may split off as some departments of the company for some strategic arrangement [26]. Zhang, *et al.* proposed that symbiotic evolution is the cornerstone of sustainable development and common prosperity between dual-agent enterprises, providing ideas for the development of innovation ecosystem [27]. Romano *et al.* studied that in the innovation ecosystem, the development of enterprises benefits from the active interaction of knowledge transfer, absorption and innovation among relevant enterprises [28]. Therefore, satellite enterprises can rely on core enterprises to develop core technologies and improve their overall competitiveness. Wu and Jin took Yutong and Beijing Automobile Co., LTD as research objects to analyze the nature and influence mechanism of predation symbiosis and mutualism in the innovation ecosystem led by core enterprises [29]. Yan and Zhang analyzed the core group of entrepreneurial enterprises and supporting enterprises and discussed the symbiotic evolution strategy mode of green innovation ecosystem [30].

B. RESEARCH ON THE KNOWLEDGE INNOVATION AND ENVIRONMENTAL SOCIAL RESPONSIBILITY EFFECT OF CORE ENTERPRISES

Generally speaking, there are one or more core enterprises in the innovation ecosystem, which form a connection and cooperation relationship with other subjects through complementary resource dependence. The deeper the cooperation, the more efficient the knowledge flow [31]. Subjects with specific network connections in the innovation ecosystem exchange knowledge resources, which forms the basis of continuous innovation iteration [32]. Internal enterprises gain benefits in innovation iteration and can obtain key technical support [24]. Cassiman and Valentini believed that knowledge resources flow bidirectionally in the innovation ecosystem, and that the main links are the acquisition, assimilation and integration of external knowledge, as well as the outflow, reorganization and business model reconstruction of internal knowledge [33]. In contrast to the traditional innovation collaboration mode, Malecki proposed that knowledge flow within the innovation ecosystem is very active and knowledge penetration among subjects is particularly obvious, but knowledge penetration is not equal to an exchange relationship [34]. Vida empirically analyzed the influencing factors of enterprise knowledge innovation by taking 150 KIBS as research objects [35]. Leydesdorff *et al.* proposed that enterprises, as the subject of innovation, take innovation and value-added as the fundamental goal and realize knowledge innovation through the management of subsystems such as knowledge sharing, absorption, transformation, application and integration [36]. Currently, there are abundant researches on knowledge innovation in innovation ecosystem in the academic circle. Boisot studied and showed that the characteristics of knowledge itself and the possibility of knowledge acceptance affect the process of knowledge flow [37]. Ounjian and Carne believed that the characteristics of technology, technology recipient, technology provider and communication channel have a direct impact on knowledge flow [38]. Michel *et al.* studied the connection between value formation and knowledge flow in the innovation ecosystem and concluded that efficient knowledge flow can significantly promote value formation [39]. Koessler proposed a general model of strategic knowledge sharing in finite Bayesian games when uncertainty was ignored [40]. Taking the community as the research object, Li and Li introduced incentive mechanism into knowledge sharing and concluded that incentive mechanism significantly improved knowledge sharing ability [41].

Research on the effect of enterprises' fulfillment of environmental social responsibility has been carried out by scholars from different perspectives. Luo and Du concluded that environmental social responsibility effectively improves the information asymmetry between enterprises and stakeholders, thus achieving good communication in the production process, reducing risks in the process of technological innovation, and further stimulating enterprises' R&D investment [42]. Through empirical analysis, Xie *et al.* proposed that a good social green image of enterprises is conducive to improving the overall income and has an important impact on the core competitiveness of enterprises [43]. Bardos *et al.*further proposed that enterprise social responsibility and enterprise value are synergistic, and the realization of value creation also positively promotes the effect of social responsibility [44]. As an important guide of the innovation ecosystem, the government usually makes corresponding policies to guide the core enterprises to carry out green technology innovation with the help of market signals. Caravella and Crespi proposed that market-oriented environmental regulations promote green process innovation and product innovation of enterprises [45]. Yang *et al.* put forward that environmental sustainability strategies formulated by enterprises for environmental issues are more important than sustainable economic development strategies for improving corporate social responsibility image [46]. Chen and Ha took Shanghai and Shenzhen A-share listed enterprises as the research object and found that the sharing of corporate social responsibility has a positive effect on the investment in technological innovation research and development, and technological innovation has a mediating effect in the relationship between enterprise social responsibility and value creation [47]. Liu and Chen analyzed the strategic choice of enterprise social responsibility and technological innovation by using the oligarchic competition game model and pointed out that with limited resources, enterprises' excessive performance of social responsibility would inhibit technological innovation, so government guidance and supervision play an important role [48].

C. LITERATURE REVIEW AND RESEARCH FRAMEWORK

Based on the existing research, it can be concluded that the innovation ecosystem provides a major theoretical basis for the study of core enterprise knowledge innovation and the fulfillment of environmental social responsibility. Previous researches of scholars focused on the innovation activities and fulfillment of environmental social responsibilities of single core enterprises, but the research on knowledge flow in the innovation ecosystem constructed by multi-core enterprises was insufficient, and scholars did not pay attention to the decision-making problems of multi-core enterprises when comprehensively considering knowledge innovation and fulfillment of environmental social responsibility in the innovation ecosystem. In fact, the relationship between the two is not simply complementary or alternative. Based on this, this paper mainly considers the following issues: (1) In the context of carbon neutrality, how can the multi-agent R&D innovation system constructed by core enterprises and satellite enterprises balance the effects of knowledge innovation and environmental social responsibility, and then maximize the overall benefits? (2) How does the knowledge innovation R&D system achieve the development goal of symbiotic evolution of innovation ecosystem under the constraint of environmental social responsibility? (3) If the satellite enterprise is dependent on or follows the core enterprise, can the revenue of the innovation R&D system of both sides reach the optimal state? (4) Can the optimal returns of both the core enterprise and the satellite enterprise be improved by making decisions independently?

In summary, this paper comprehensively considers the effects of knowledge innovation and environmental social responsibility. Based on the theories of core competence, symbiotic evolution and game theory, this paper constructs differential game equations for knowledge innovation of R&D innovation system under three types of situations, and abstractly describes the enterprise innovation ecosystem. In addition, the optimal revenue of core enterprises and satellite enterprises under the three decisions is compared with the overall revenue, and then the optimal collaborative innovation mode is selected. Finally, the influence factors of the three scenarios are simulated and analyzed, and specific countermeasures and suggestions are put forward based on the actual situation, in order to provide some references for selecting knowledge innovation strategies in the multi-core enterprise-led innovation ecosystem.

III. PROBLEM DESCRIPTION AND MODEL CONSTRUCTION

1) PROBLEM DESCRIPTION

The enterprise green innovation ecosystem is a complex and large system, which is composed of the government, enterprises, universities and institutes, intermediary institutions and other participants under the green economic ecological mode with low pollution, low energy consumption and low emissions as the standard, and aims to achieve ecological environmental protection [49]. Assume that the research object of this paper is the knowledge innovation R&D system of enterprise green innovation ecosystem that is composed of core enterprises and satellite enterprises with completely rational and symmetric information, as shown in Fig. 1. There is a synergistic connection between the core enterprises with independent behavior and decision-making and the satellite enterprises. With the goal of maximizing

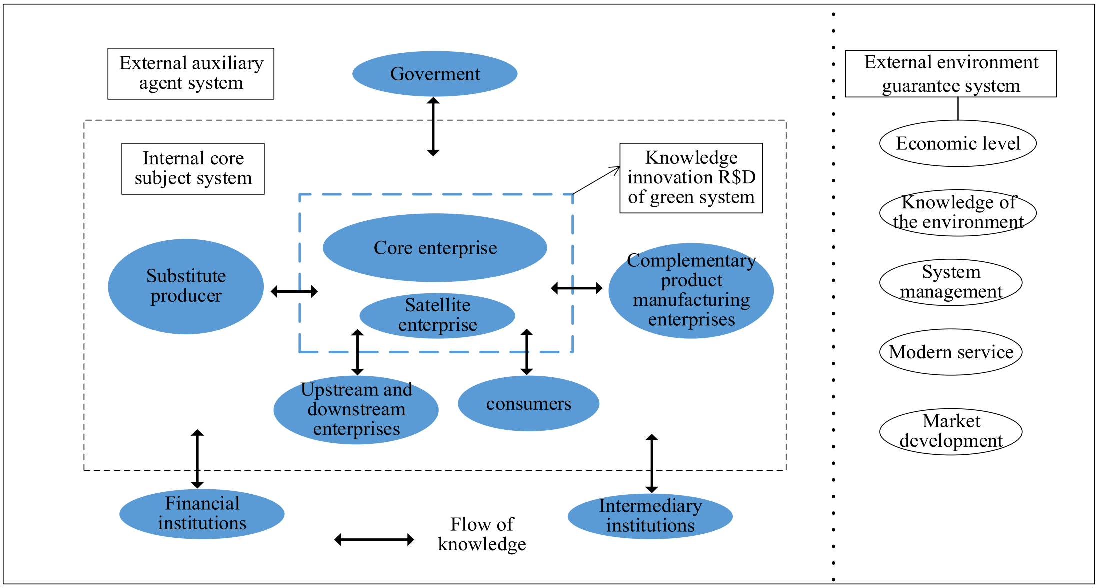

FIGURE 1. **Knowledge flow structure of enterprise green innovation ecosystem.**

profits, the efficient flow of knowledge can be achieved through collaborative innovation, knowledge capture and sharing, and the R&D level can be continuously improved. Core enterprises have absolute leadership, rich resources and good social reputation in the innovation ecosystem. In the process of green technology innovation research and development, there will be spillover effect of learning and imitation of satellite enterprises. Under the carbon neutral strategic goal, the government will subsidize knowledge innovation and reward the fulfillment of environmental social responsibility. At this time, the enthusiasm of core enterprises and satellite enterprises will be greatly increased. Therefore, the first scenario is that the R&D innovation system composed of core enterprises and satellite enterprises pursues the maximization of overall interests and chooses collaborative knowledge innovation, which is in line with centralized decision-making. The second scenario is that the core enterprise and the satellite enterprise are in an equal position and make decisions independently but promote the development of the core system of knowledge innovation in the green innovation ecosystem together, that is, to meet the decentralized decision-making. The third Scenario is that the satellite enterprise will follow the core enterprise to conduct green technology research and development, and the Stackelberg's master-slave game decision is satisfied.

2) MODEL CONSTRUCTION

On the premise of considering knowledge innovation and environmental social responsibility, this paper uses three differential game methods, namely centralized decision making, decentralized decision making and Stackelberg master-slave game, to study the different decision-making behaviors of core enterprises and satellite enterprises. Parameters involved in the three differential game models and their meanings are shown in Tab. 1.

Combined with the principle of marginal effect, the cost of knowledge innovation R&D and the cost of fulfilling environmental social responsibility have the same convexity characteristic. This paper uses a quadratic function to describe the cost. At time t, the cost function of core enterprise and satellite enterprise on knowledge innovation R&D and fulfilling environmental social responsibility is as follows:

$$C_{D_i}(t) = \frac{\alpha_{D_i}}{2} D_i^2(t) \tag{1}$$

$$C_{E_i}(t) = \frac{\alpha_{E_i}}{2} E_i^2(t) \tag{2}$$

Among them, $i = \{M, N\}$.

In order to maintain the core competitiveness of enterprise green innovation ecosystem, core enterprises and satellite enterprises tend to acquire frontier knowledge, and the core ways of acquiring frontier knowledge are knowledge capture and knowledge sharing. At the same time, in consideration of social reputation and obtaining more resources through the effect of environmental social responsibility, both core enterprises and satellite enterprises attach more importance to fulfilling social environmental responsibility. In this process, the knowledge level and social environmental responsibility effect in the R&D system composed of core enterprises and satellite enterprises are in a dynamic process of change. Therefore, the differential equation of collaborative R&D of decision-making bodies is:

$$T'(t) = \frac{dT(t)}{dt} = \beta_M D_M(t) + \beta_N D_N(t) - \delta T(t) \tag{3}$$

$$S'(t) = \frac{dS(t)}{dt} = \chi_M E_M(t) + \chi_N E_N(t) - \varepsilon S(t) \tag{4}$$

TABLE 1. Parameter symbols and meanings.

symbols	meanings
M	Core enterprise.
N	Satellite enterprise.
D_i	The degree of knowledge innovation effort of enterprise i, $i\in\{M,N\}$.
E_i	The degree of effort of enterprise i in fulfilling its environmental social responsibility, $i\in\{M,N\}$.
α_{D_i}	The effort cost coefficient of enterprise i in knowledge innovation, $i\in\{M,N\}$.
α_{E_i}	The effort cost coefficient of enterprise i in fulfilling its environmental social responsibility, $i\in\{M,N\}$.
σ_i	The subsidy rate given by the government to enterprise i for knowledge innovation R&D, $i\in\{M,N\}$.
$T(t)$	The knowledge innovation research and development level of the core system of enterprise green innovation ecosystem at moment t.
$S(t)$	The environmental effect of the core system of the enterprise green innovation ecosystem at moment t to fulfill its environmental social responsibility.
H_M	The objective function of core enterprise.
H_N	The objective function of satellite enterprise.
ω_i	The government's support for enterprise i to fulfill its environmental social responsibilities, $i\in\{M,N\}$.
β_M	The influence degree of core enterprise knowledge innovation R&D effort on technology level.
β_N	The influence degree of knowledge innovation R&D effort of satellite enterprises on technology level.
χ_M	The degree of impact of core enterprise's fulfillment of environmental responsibility on environmental social effect.
χ_N	The degree of impact of satellite enterprise's fulfillment of environmental responsibility on environmental social effect.
η	The influence of the main enterprise's efforts in knowledge innovation R&D on the total revenue.
μ	The influence of the main enterprise's efforts in fulfilling environmental social responsibility on the total income.
δ	Knowledge depreciation rate, $\delta\ge 0$.
ε	The negative influence of enterprise's excessive performance of social environmental responsibility on enterprise development, $\varepsilon\ge 0$.
π_0	Initial yield, $\pi_0\ge 0$.
p	The proportion of revenue earned by core enterprise, $0\le p\le 1$.
ρ	The discount rate at time 0 to t, $\rho>0$.

IV. MODEL ANALYSIS

A. CENTRALIZED DECISION MAKING

Centralized decision-making emphasizes the profit maximization of the core enterprise and the satellite enterprise as a whole, that is, the R&D innovation system will cooperate to determine the healthy development level of the enterprise green innovation ecosystem, with the overall profit maximization of both parties as the goal, so as to improve the core competitiveness of the whole system. At this point, the decision-making objective is:

$$\begin{aligned}\Pi &= H_M + H_N \\ &= \max_{D_i\ge 0,E_i\ge 0}\int_0^{+\infty}[e^{-\rho t}\pi(t)-\frac{\alpha_{D_M}}{2}(1-\sigma_M)D_M^2-\frac{\alpha_{E_M}}{2} \\ &\quad\times(1-\omega_M)E_M^2-\frac{\alpha_{D_N}}{2}(1-\sigma_N)D_N^2-\frac{\alpha_{E_N}}{2}(1-\omega_N)E_N^2]dt\end{aligned} \tag{5}$$

Among them, $i=\{M,N\}$

Theorem 1: Equilibrium results of core enterprises and satellite enterprises under centralized decision-making are as follows:

(1) The optimal equilibrium of core enterprises is:

$$(D_M^c, E_M^c) = \left(\frac{\beta_M\eta}{\alpha_{D_M}(1-\sigma_M)(\rho+\delta)}, \frac{\chi_M\mu}{\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)}\right) \tag{6}$$

(2) The optimal equilibrium of satellite enterprises is:

$$(D_N^c, E_N^c) = \left(\frac{\beta_N\eta}{\alpha_{D_N}(1-\sigma_N)(\rho+\delta)}, \frac{\chi_N\mu}{\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)}\right) \tag{7}$$

Proof: The dynamic random control method is adopted to solve the problem. After time t, the most valuable function of the overall long-term profits of core enterprises and satellite enterprises is $\Pi(T,S) = e^{-\rho t}V(T,S)$. In the range of $T\ge 0, S\ge 0$, $V(T,S)$ satisfies the HJB equation.

$$\begin{aligned}\rho V(T,S) &= \max_{D_i\ge 0,E_i\ge 0}[(\pi_0+\eta T+\mu S)-\frac{\alpha_{D_M}}{2}(1-\sigma_M)D_M^2-\frac{\alpha_{E_M}}{2} \\ &\quad\times(1-\omega_M)E_M^2-\frac{\alpha_{D_N}}{2}(1-\sigma_N)D_N^2-\frac{\alpha_{E_N}}{2}(1-\omega_N)E_N^2 \\ &\quad+\frac{\partial V}{\partial T}(\beta_M D_M+\beta_N D_N-\delta T)+\frac{\partial V}{\partial S}(\chi_M E_M+\chi_N E_N-\varepsilon S)]\end{aligned} \tag{8}$$

Among them, $i\in\{M,N\}$.

Equation (8) is the concave function of (D_M, E_M) and (D_N, E_N), and the optimal strategy of the core enterprise and the satellite enterprise can be obtained from the first-order condition:

$$(D_M, E_M) = \left(\frac{\beta_M\frac{\partial V}{\partial T}}{(1-\sigma_M)\alpha_{D_M}}, \frac{\chi_M\frac{\partial V}{\partial S}}{(1-\omega_M)\alpha_{E_M}}\right) \tag{9}$$

$$(D_N, E_N) = \left(\frac{\beta_N\frac{\partial V}{\partial T}}{(1-\sigma_N)\alpha_{D_N}}, \frac{\chi_N\frac{\partial V}{\partial S}}{(1-\omega_N)\alpha_{E_N}}\right) \tag{10}$$

By substituting (9) and (10) into (8), we can obtain

$$\begin{aligned}\rho V(T,S) &= \pi_0+(\eta-\delta\frac{\partial V}{\partial T})T+(\mu-\varepsilon\frac{\partial V}{\partial S})S \\ &\quad+\frac{\beta_M^2(\frac{\partial V}{\partial T})^2}{2(1-\sigma_M)\alpha_{D_M}}+\frac{\chi_M^2(\frac{\partial V}{\partial S})^2}{2(1-\omega_M)\alpha_{E_M}} \\ &\quad+\frac{\beta_N^2(\frac{\partial V}{\partial T})^2}{2(1-\sigma_N)\alpha_{D_N}}+\frac{\chi_N^2(\frac{\partial V}{\partial S})^2}{2(1-\omega_N)\alpha_{E_N}}\end{aligned} \tag{11}$$

Analysis of (11) shows that the solution of Hamilton–Jacobi–Bellman (HJB) Equation is a linear function of T and S, let

$$V(T,S) = a_1 T + b_1 S + c_1 \tag{12}$$

where a_1, b_1 and c_1 are all constants, the following equation can be obtained

$$a_1 = \frac{\eta}{\rho+\delta}$$
$$b_1 = \frac{\mu}{\rho+\varepsilon}$$
$$c_1 = \frac{\pi_0}{\rho} + \left[\frac{\beta_M^2}{2\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{\beta_N^2}{2\rho\alpha_{D_N}(1-\sigma_N)(\rho+\delta)^2}\right]\eta^2 + \left[\frac{\chi_M^2}{2\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} + \frac{\chi_N^2}{2\rho\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)^2}\right]\mu^2 \quad (13)$$

Substituting (13) into (9) and (10) to obtain the optimal equilibrium strategy, namely, (6) and (7). Then, by substituting (6) and (7) into (3) and (4), the optimal evolution trajectory of knowledge innovation level and environmental social responsibility effect of enterprise green innovation ecosystem can be obtained:

$$T^C = K_1 + (T_0 - K_1)e^{-\delta t} \quad (14)$$
$$S^C = K_2 + (S_0 - K_2)e^{-\varepsilon t} \quad (15)$$

Among them, $K_1 = \frac{\eta\beta_M^2}{\delta\alpha_{D_M}(1-\sigma_M)(\rho+\delta)} + \frac{\eta\beta_N^2}{\delta\alpha_{D_N}(1-\sigma_N)(\rho+\delta)}$, $K_2 = \frac{\mu\chi_M^2}{\varepsilon\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)} + \frac{\mu\chi_N^2}{\varepsilon\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)}$.

By substituting (13) into (12), the optimal profit function of core enterprises and satellite enterprises in the enterprise green innovation ecosystem under centralized decision making can be obtained, and then the total profit of the system can be obtained:

$$V^c = \frac{\eta}{\rho+\delta}T^C + \frac{\mu}{\rho+\varepsilon}S^C + \frac{\pi_0}{\rho} + \left[\frac{\beta_M^2}{2\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{\beta_N^2}{2\rho\alpha_{D_N}(1-\sigma_N)(\rho+\delta)^2}\right]\eta^2 + \left[\frac{\chi_M^2}{2\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} + \frac{\chi_N^2}{2\rho\alpha_{D_N}(1-\omega_N)(\rho+\varepsilon)^2}\right]\mu^2 \quad (16)$$

End of Proof.

B. DECENTRALIZED DECISION MAKING

Decentralized decision-making emphasizes that core enterprises and satellite enterprises in the enterprise green innovation ecosystem independently choose their respective strategies at the same time to maximize the objective function. At this point, their respective objective function is:

$$H_M = \max_{D_M\geq 0, E_M\geq 0}\int_0^{+\infty} e^{-\rho t}[p\pi(t) - \frac{\alpha_{D_M}}{2}(1-\sigma_M)D_M^2 - \frac{\alpha_{E_M}}{2}(1-\omega_M)E_M^2]dt \quad (17)$$
$$H_N = \max_{D_N\geq 0, E_N\geq 0}\int_0^{+\infty} e^{-\rho t}[(1-p)\pi(t) - \frac{\alpha_{D_N}}{2}(1-\sigma_N)D_N^2 - \frac{\alpha_{E_N}}{2}(1-\omega_N)E_N^2]dt \quad (18)$$

Theorem 2: The optimal strategy of core enterprise and satellite enterprise in the case of independent decision-making is

$$(D_M^n, E_M^n) = (\frac{p\beta_M\eta}{\alpha_{D_M}(1-\sigma_M)(\rho+\delta)}, \frac{p\chi_M\mu}{\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)}) \quad (19)$$
$$(D_N^n, E_N^n) = (\frac{(1-p)\beta_N\eta}{\alpha_{D_N}(1-\sigma_N)(\rho+\delta)}, \frac{(1-p)\chi_N\mu}{\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)}) \quad (20)$$

Proof: The dynamic random control method is adopted to solve the problem. The return function of enterprise i is denoted as $V_i(T, S)$, $i \in \{M, N\}$ is continuously bounded and differentiable, and all $T \geq 0$, $S \geq 0$ satisfy the HJB equation:

$$\rho V_M(T,S) = \max_{D_M\geq 0, E_M\geq 0}[p(\pi_0 + \eta T + \mu S) - \frac{1}{2}(1-\sigma_M)\alpha_{D_M}D_M^2 - \frac{1}{2}(1-\omega_M)\alpha_{E_M}E_M^2 + \frac{\partial V_M}{\partial T}(\beta_M D_M + \beta_N D_N - \delta T) + \frac{\partial V_M}{\partial S}(\chi_M E_M + \chi_N E_N - \varepsilon S)] \quad (21)$$
$$\rho V_N(T,S) = \max_{D_N\geq 0, E_N\geq 0}[(1-p)(\pi_0 + \eta T + \mu S) - \frac{1}{2}(1-\sigma_N)\alpha_{D_N}D_N^2 - \frac{1}{2}(1-\omega_N)\alpha_{E_N}E_N^2 + \frac{\partial V_N}{\partial T}(\beta_M D_M + \beta_N D_N - \delta T) + \frac{\partial V_M}{\partial S}(\chi_M E_M + \chi_N E_N - \varepsilon S)] \quad (22)$$

According to the first-order conditions of (21) and (22), the optimal strategy of core enterprises and satellite enterprises is

$$(D_M, E_M) = \left(\frac{\beta_M\frac{\partial V_M}{\partial T}}{(1-\sigma_M)\alpha_{D_M}}, \frac{\chi_M\frac{\partial V_M}{\partial S}}{(1-\omega_M)\alpha_{E_M}}\right) \quad (23)$$
$$(D_N, E_N) = \left(\frac{\beta_N\frac{\partial V_N}{\partial T}}{(1-\sigma_N)\alpha_{D_N}}, \frac{\chi_N\frac{\partial V_N}{\partial S}}{(1-\omega_N)\alpha_{E_N}}\right) \quad (24)$$

By substituting (23) and (24) into (21) and (22), we can obtain

$$\rho V_M(T,S) = p\pi_0 + \left(p\eta - \delta\frac{\partial V_M}{\partial T}\right)T + \left(p\mu - \varepsilon\frac{\partial V_M}{\partial S}\right)S + \frac{\left(\beta_M\frac{\partial V_M}{\partial T}\right)^2}{2\alpha_{D_M}(1-\sigma_M)} + \frac{\left(\chi_M\frac{\partial V_M}{\partial S}\right)^2}{2\alpha_{E_M}(1-\omega_M)} + \frac{\beta_N^2\frac{\partial V_M}{\partial T}\frac{\partial V_N}{\partial T}}{\alpha_{D_N}(1-\sigma_N)} + \frac{\chi_N^2\frac{\partial V_M}{\partial S}\frac{\partial V_N}{\partial S}}{\alpha_{E_N}(1-\omega_N)} \quad (25)$$

$$\rho V_N(T,S) = (1-p)\pi_0 + \left((1-p)\eta - \delta\frac{\partial V_N}{\partial T}\right)T + \left((1-p)\mu - \varepsilon\frac{\partial V_N}{\partial S}\right)S + \frac{\left(\beta_N\frac{\partial V_N}{\partial T}\right)^2}{2\alpha_{D_N}(1-\sigma_N)} + \frac{\left(\chi_N\frac{\partial V_N}{\partial S}\right)^2}{2\alpha_{E_N}(1-\omega_N)} + \frac{\beta_M^2\frac{\partial V_M}{\partial T}\frac{\partial V_N}{\partial T}}{\alpha_{D_M}(1-\sigma_M)} + \frac{\chi_M^2\frac{\partial V_M}{\partial S}\frac{\partial V_N}{\partial S}}{\alpha_{E_M}(1-\omega_M)} \quad (26)$$

By analyzing (25) and (26), it can be deduced that the solution of hjb equation is a binary function about sum, let

$$V_M(T,S) = a_2T + b_2S + c_2 \quad (27)$$
$$V_N(T,S) = a_3T + b_3S + c_3 \quad (28)$$

where $a_2, a_3, b_2, b_3, c_2, c_3$ are constants and can be deduced

$$a_2 = \frac{p\eta}{\rho+\delta}$$
$$a_3 = \frac{(1-p)\eta}{\rho+\delta}$$
$$b_2 = \frac{p\mu}{\rho+\varepsilon}$$
$$b_3 = \frac{(1-p)\mu}{\rho+\varepsilon}$$
$$c_2 = \frac{p\pi_0}{\rho} + \left[\frac{p^2\beta_M^2}{2\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{p(1-p)\beta_N^2}{\rho\alpha_{D_N}(1-\sigma_N)(\rho+\delta)^2}\right]\eta^2 + \left[\frac{p^2\chi_M^2}{2\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} + \frac{p(1-p)\chi_N^2}{\rho\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)^2}\right]\mu^2$$
$$c_3 = \frac{(1-p)\pi_0}{\rho} + \left[\frac{p(1-p)\beta_M^2}{\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{(1-p)^2\beta_N^2}{2\rho\alpha_{D_N}(1-\sigma_N)(\rho+\delta)^2}\right]\eta^2 + \left[\frac{p(1-p)\chi_M^2}{\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} + \frac{(1-p)^2\chi_N^2}{2\rho\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)^2}\right]\mu^2 \quad (29)$$

By substituting (29) into (23) and (24), the optimal equilibrium strategy can be obtained, namely, (19) and (20). Then, by substituting (19) and (20) into (3) and (4), the optimal evolution trajectory of knowledge innovation level and Environmental social responsibility effect of enterprise green innovation ecosystem can be obtained:

$$T^n = K_2 + (T_0 - K_2)e^{-\delta t} \quad (30)$$
$$S^n = K_3 + (S_0 - K_3)e^{-\varepsilon t} \quad (31)$$

Among them, $K_2 = \frac{\eta p\beta_M^2}{\delta\alpha_{D_M}(1-\sigma_M)(\rho+\delta)} + \frac{\eta(1-p)\beta_N^2}{\delta\alpha_{D_N}(1-\sigma_N)(\rho+\delta)}$, $K_3 = \frac{\mu p\chi_M^2}{\varepsilon\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)} + \frac{\mu(1-p)\chi_N^2}{\varepsilon\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)}$.

By Substituting (29) into (27) and (28) to obtain the optimal revenue function of core enterprises and satellite enterprises in the enterprise green innovation ecosystem under centralized decision-making, and then the total profit of the system is reached as follows:

$$V^n = \frac{\eta}{\rho+\delta}T^n + \frac{\mu}{\rho+\varepsilon}S^n + \frac{\pi_0}{\rho} + \left[\frac{p(2-p)\beta_M^2}{2\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{(1-p^2)\beta_N^2}{2\rho\alpha_{D_N}(1-\sigma_N)(\rho+\delta)^2}\right]\eta^2 + \left[\frac{p(2-p)\chi_M^2}{2\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} + \frac{(1-p^2)\chi_N^2}{2\rho\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)^2}\right]\mu^2 \quad (32)$$

End of proof.

C. STACKELBERG MASTER-SLAVE GAME

Core enterprises have absolute leadership in the enterprise green innovation ecosystem, and they also need to pay more costs to maintain the healthy development of the system. In the Stackelberg master-follower game scenario, in order to encourage the cooperative innovation of satellite enterprises, the core enterprise will bear a certain proportion of the R&D cost of knowledge innovation and the cost of green environmental responsibility, and the proportion of sharing is set as b_D and b_E respectively. The core enterprise first decides its own effort level, and then the satellite enterprise chooses its own effort level after observing the actions of the core enterprise. At this point, the optimal strategies of both parties are $\left(D_M^s, E_M^s\right)$ and $\left(D_N^s, E_N^s\right)$, and the objective functions of both parties are as follows:

$$H_M = \max_{D_M\geq 0, D_M\geq 0}\int_0^{+\infty} e^{-\rho t}[p\pi(t) - \frac{\alpha_{D_M}}{2}(1-\sigma_M)D_M^2 - \frac{\alpha_{E_M}}{2}(1-\omega_M)E_M^2 - \frac{\alpha_{D_N}b_D}{2}(1-\sigma_N)D_N^2 - \frac{\alpha_{E_M}b_E}{2}(1-\omega_M)E_M^2]dt \quad (33)$$

$$H_N = \max_{D_N\geq 0, E_N\geq 0}\int_0^{+\infty} e^{-\rho t}[(1-p)\pi(t) - \frac{\alpha_{D_N}}{2}(1-\sigma_N-b_D)D_N^2 - \frac{\alpha_{E_N}}{2}(1-\omega_N-b_E)E_N^2]dt \quad (34)$$

Theorem 3: In Stackelberg master-slave game between core enterprises and satellite enterprises, the optimal decision of both parties is as follows:

$$\left(D_M^s, E_M^s\right) = \left(\frac{p\beta_M\eta}{\alpha_{D_M}(1-\sigma_M)(\rho+\delta)}, \frac{p\chi_M\mu}{\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)}\right) \quad (35)$$

$$(D_N^s, E_N^s) = \left(\frac{\beta_N \eta \left[2p + (1-p)(1-\sigma_N)\right]}{2\alpha_{D_N}(1-\sigma_N)^2(\rho+\delta)}, \frac{\chi_N \mu \left[2p + (1-p)(1-\omega_N)\right]}{2\alpha_{E_N}(1-\omega_N)^2(\rho+\varepsilon)} \right) \quad (36)$$

$$b_D^s = \frac{2p\left(1-\sigma_N\right) - \left(1-\sigma_N\right)^2\left(1-p\right)}{2p + \left(1-\sigma_N\right)\left(1-p\right)}, \quad \frac{1-\sigma_N}{3-\sigma_N} < p < 1 \quad (37)$$

$$b_E^s = \frac{2p\left(1-\omega_N-\theta_N\right) - \left(1-\omega_N\right)^2\left(1-p\right)}{2p + \left(1-\omega_M\right)\left(1-p\right)}, \quad \frac{1-\omega_N}{3-\omega_N} < p < 1 \quad (38)$$

When $0 < p < \frac{1-\sigma_N}{3-\sigma_N}, b_D^s = 0$, and when $0 < p < \frac{1-\omega_N}{3-\omega_N} b_E^s = 0$

Proof: The inverse regression method was used to solve the model. The core enterprise's strategy is (D_M, E_M, b_D, b_E). As rational decision-makers, satellite enterprises make decisions on their own effort level after the core enterprises make the optimal choice. The income function $V_i(T, S)$ of enterprise i is continuously bounded and differentiable, and all $T \geq 0, S \geq 0$ satisfy the HJB equation. It can be concluded:

$$\begin{aligned}\rho V_M(T,S) = \max_{D_M \geq 0, D_M \geq 0} & [p(\pi_0 + \eta T + \mu S) \\ & - \frac{\alpha_{D_M}}{2}\left(1-\sigma_M\right)D_M^2 - \frac{\alpha_{E_M}}{2}\left(1-\omega_M\right)E_M^2 \\ & - \frac{\alpha_{D_N} b_D}{2}(1-\sigma_N)D_N^2 - \frac{\alpha_{E_N} b_E}{2}(1-\omega_N)E_N^2 \\ & + \frac{\partial V_M}{\partial T}(\beta_M D_M + \beta_N D_N - \delta T) \\ & + \frac{\partial V_M}{\partial S}(\chi_M E_M + \chi_N E_N - \varepsilon S)]\end{aligned} \quad (39)$$

$$\begin{aligned}\rho V_N(T,S) = \max_{D_N \geq 0, E_N \geq 0} & [(1-p)(\pi_0 + \eta T + \mu S) \\ & - \frac{\alpha_{D_N}}{2}\left(1-\sigma_N-b_D\right)D_N^2 - \frac{\alpha_{E_N}}{2}\left(1-\omega_N-b_E\right) \\ & \times E_N^2 + \frac{\partial V_N}{\partial T}(\beta_M D_M + \beta_N D_N - \delta T) \\ & + \frac{\partial V_N}{\partial S}(\chi_M E_M + \chi_N E_N - \varepsilon S)]\end{aligned} \quad (40)$$

Equations (39) and (40) are convex functions. Based on first-order conditions, the optimal strategy can be obtained:

$$(D_M, E_M) = \left(\frac{\beta_M \frac{\partial V_M}{\partial T}}{\alpha_{D_M}(1-\sigma_M)}, \frac{\chi_M \frac{\partial V_M}{\partial S}}{\alpha_{E_M}\left(1-\omega_M\right)} \right) \quad (41)$$

$$(D_N, E_N) = \left(\frac{\beta_N \frac{\partial V_N}{\partial T}}{\alpha_{D_N}(1-\sigma_N-b_D)}, \frac{\chi_N \frac{\partial V_N}{\partial S}}{\alpha_{E_N}\left(1-\omega_N-b_E\right)} \right) \quad (42)$$

$$b_D = \frac{2\left(1-\sigma_N\right)\left(\frac{\partial V_M}{\partial T}\right) - \left(1-\sigma_N\right)^2\left(\frac{\partial V_N}{\partial T}\right)}{2\left(\frac{\partial V_M}{\partial T}\right) + \left(1-\sigma_N\right)\left(\frac{\partial V_N}{\partial T}\right)} \quad (43)$$

$$b_E = \frac{2\left(1-\omega_N-\theta_N\right)\left(\frac{\partial V_M}{\partial S}\right) - \left(1-\omega_N\right)^2\left(\frac{\partial V_N}{\partial S}\right)}{2\left(\frac{\partial V_M}{\partial S}\right) + \left(1-\omega_M\right)\left(\frac{\partial V_N}{\partial S}\right)} \quad (44)$$

By substituting (41), (42), (43) and (44) into (39) and (40), we can obtain (45)–(48), as shown at the bottom of the next page, where $a_4, a_5, b_4, b_5, c_4, c_5$ are constants and can be deduced

$$\begin{aligned} a_4 &= \frac{p\eta}{\rho+\delta} \\ b_4 &= \frac{p\mu}{\rho+\varepsilon} \\ a_5 &= \frac{(1-p)\eta}{\rho+\delta} \\ b_5 &= \frac{(1-p)\mu}{\rho+\varepsilon} \\ c_4 &= \frac{p\pi_0}{\rho} + \left\{ \frac{p^2\beta_M^2}{2\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{\beta_N^2\left[4p^2+4p(1-p)\left(1-\sigma_N\right)+(1-p)^2(1-\sigma_N)^2\right]}{8\rho\alpha_{D_N}(1-\sigma_N)^2(\rho+\delta)^2} \right\}\eta^2 \\ & \quad + \left\{ \frac{p^2\chi_M^2}{2\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} + \frac{\chi_N^2\left[4p^2+4p(1-p)(1-\omega_N)+(1-p)^2(1-\omega_N)^2\right]}{8\rho\alpha_{E_N}(1-\omega_N)^2(\rho+\varepsilon)^2} \right\}\mu^2 \\ c_5 &= \frac{(1-p)\pi_0}{\rho} + \left[\frac{p(1-p)\beta_M^2}{\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{(1-p)^2\beta_N^2}{4\rho\alpha_{D_N}(1-\sigma_N)^2(\rho+\delta)^2} \right]\eta^2 \\ & \quad + \left[\frac{p(1-p)\chi_M^2}{\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} + \frac{(1-p)^2\chi_N^2}{4\rho\alpha_{E_N}(1-\omega_N)^2(\rho+\varepsilon)^2} \right]\mu^2 \end{aligned} \quad (49)$$

By substituting (49) into (43) and (44), the optimal strategy of both parties and the optimal cost sharing ratio b_D and b_E of the core enterprise as the supporting enterprise can be obtained. By substituting the results into (3) and (4) and solving them, the optimal evolution trajectory of knowledge innovation R&D level and environmental social responsibility effect can be obtained:

$$T^s = K_4 + (T_0 - K_4)e^{-\delta t} \quad (50)$$

$$S^s = K_5 + (S_0 - K_5)e^{-\varepsilon t} \quad (51)$$

Among them, $K_4 = \frac{\eta p \beta_M^2}{\delta\alpha_{D_M}(1-\sigma_M)(\rho+\delta)} + \frac{\eta\beta_N^2[2p+(1-p)(1-\sigma_N)]}{2\delta\alpha_{D_N}(1-\sigma_N)^2(\rho+\delta)}$, $K_5 = \frac{\mu p \chi_M^2}{\varepsilon\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)} + \frac{\mu\chi_N^2[2p+(1-p)(1-\omega_N)]}{2\varepsilon\alpha_{E_N}(1-\omega_N)^2(\rho+\varepsilon)}$.

By Substituting each value in (49) into (41) and Equation (42) to obtain the optimal function of core enterprise and satellite enterprise respectively, the optimal value of total profit of R&D innovation system of enterprise green innovation ecosystem under Stackelberg master-slave game is as follows (52), as shown at the bottom of the page.

End of proof.

D. COMPARATIVE ANALYSIS OF THE RESULTS OF THE THREE GAME SCENARIOS

Through comparative analysis of the optimal strategies and benefits of core enterprises and satellite enterprises under the three game scenarios, as well as the knowledge innovation level and benefits of the R&D innovation system constructed by both sides, the following propositions are obtained.

Proposition 1: The comparative analysis results of optimal strategies of core enterprises and satellite enterprises under the three game modes are as follows:

$D_M^c > D_M^s = D_M^n, E_M^c > E_M^s = E_M^n, D_N^c > D_N^n, E_N^c > E_N^n$, and when $\frac{1}{3} < p < 1, D_N^s > D_N^n, E_N^s > E_N^n$.

Proof:

$$D_M^c - D_M^s = \frac{\beta_M \eta}{\alpha_{D_M}(1-\sigma_M)(\rho+\delta)} - \frac{p\beta_M \eta}{\alpha_{D_M}(1-\sigma_M)(\rho+\delta)} = \frac{(1-p)\beta_M \eta}{\alpha_{D_M}(1-\sigma_M)(\rho+\delta)} > 0$$

$$\begin{aligned}
\rho V_M(T,S) = {} & p(\pi_0 + \eta T + \mu S) \\
& + \frac{\beta_M^2 \frac{\partial V_M}{\partial T}^2}{2\alpha_{D_M}(1-\sigma_M)} + \frac{\chi_M^2 \left(\frac{\partial V_M}{\partial S}\right)^2}{\alpha_{E_M}(1-\omega_M)} \\
& - \frac{\beta_N^2 \left[2(1-\sigma_N)\frac{\partial V_M}{\partial T} - (1-\sigma_N)^2\left(\frac{\partial V_N}{\partial T}\right)\right]\left[2\frac{\partial V_M}{\partial T} + (1-\sigma_N)\left(\frac{\partial V_N}{\partial T}\right)\right]}{8\alpha_{D_n}(1-\sigma_N)^3} \\
& + \frac{\beta_N^2 \frac{\partial V_M}{\partial T}\left[2\frac{\partial V_M}{\partial T} + (1-\sigma_N)\left(\frac{\partial V_N}{\partial T}\right)\right]}{2\alpha_{D_N}(1-\sigma_N)^2} \\
& + \frac{\chi_N^2 \frac{\partial V_M}{\partial S}\left[2\frac{\partial V_M}{\partial S} + (1-\omega_N)\left(\frac{\partial V_N}{\partial T}\right)\right]}{2\alpha_{E_N}(1-\omega_N)^2} \\
& - \frac{\chi_N^2 \left[2\left((1-\omega_N)\frac{\partial V_M}{\partial S} - (1-\omega_N)^2\right)\left(\frac{\partial V_N}{\partial S}\right)\right]\left[2\frac{\partial V_M}{\partial S} + (1-\omega_N)\frac{\partial V_N}{\partial S}\right]}{8\alpha_{E_N}(1-\omega_N)^3} \\
& - \delta T \frac{\partial V_M}{\partial T} - \varepsilon S \frac{\partial V_M}{\partial S}
\end{aligned} \tag{45}$$

$$\begin{aligned}
\rho V_N(T,S) = {} & (1-p)(\pi_0 + \eta T + \mu S) + \frac{\beta_N^2 \frac{\partial V_N}{\partial T}\left[2\frac{\partial V_M}{\partial T} + (1-\sigma_N)\left(\frac{\partial V_N}{\partial T}\right)\right]}{4\alpha_{D_N}(1-\sigma_N)^2} \\
& + \frac{\chi_N^2 \frac{\partial V_N}{\partial S}\left[2\frac{\partial V_M}{\partial S} + (1-\omega_N)\left(\frac{\partial V_N}{\partial S}\right)\right]}{4\alpha_{E_N}(1-\omega_N)^2} \\
& + \frac{\beta_M^2 \frac{\partial V_M}{\partial T}\frac{\partial V_N}{\partial T}}{\alpha_{D_M}(1-\sigma_M)} + \frac{\chi_M^2 \frac{\partial V_M}{\partial S}\frac{\partial V_N}{\partial S}}{\alpha_{E_M}(1-\omega_M)} - \delta T \frac{\partial V_N}{\partial T} - \varepsilon S \frac{\partial V_N}{\partial S}
\end{aligned} \tag{46}$$

$$V_M(T,S) = a_4 T + b_4 S + c_4 \tag{47}$$

$$V_N(T,S) = a_5 T + b_5 S + c_5 \tag{48}$$

$$\begin{aligned}
V^s = {} & \frac{\eta}{\rho+\delta} T^s + \frac{\mu}{\rho+\varepsilon} S^s + \frac{\pi_0}{\rho} \\
& + \frac{p(2-p)\beta_M^2 \eta^2}{2\rho\alpha_{D_M}(1-\sigma_M)(\rho+\delta)^2} + \frac{p(2-p)\chi_M^2 \mu^2}{2\rho\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)^2} \\
& + \frac{\left[4p^2 + 4p(1-p)(1-\sigma_N) + (1-p)^2(1-\sigma_N)^2 + 2(1-p)^2\right]\beta_N^2 \eta}{8\rho\alpha_{D_N}(1-\sigma_N)^2(\rho+\delta)^2} \\
& + \frac{\left[4p^2 + 4p(1-p)(1-\omega_N) + (1-p)^2(1-\omega_N)^2 + 2(1-p)^2\right]\chi_N^2 \mu}{8\rho\alpha_{E_N}(1-\omega_N)^2(\rho+\varepsilon)^2}
\end{aligned} \tag{52}$$

$$E_M^c - E_M^s = \frac{\chi_M \mu}{\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)} - \frac{p\chi_M \mu}{\alpha_{E_M}(1-\omega_M)(\rho+\varepsilon)} = \frac{(1-p)\chi_M \mu}{\alpha_{E_M}(1-\omega_M)(\rho+\theta)} > 0$$

$$D_N^c - D_N^n = \frac{\beta_N \eta}{\alpha_{D_N}(1-\sigma_N)(\rho+\delta)} - \frac{(1-p)\beta_N \eta}{\alpha_{D_N}(1-\sigma_N)(\rho+\delta)} = \frac{p\beta_N \eta}{\alpha_{D_N}(1-\sigma_N)(\rho+\delta)} > 0$$

$$E_N^c - E_N^{\mathrm{n}} = \frac{\chi_M \mu}{\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)} - \frac{(1-p)\chi_M \mu}{\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)} = \frac{p\chi_M \mu}{\alpha_{E_N}(1-\omega_N)(\rho+\varepsilon)} > 0$$

$$D_N^s - D_N^n = \frac{\beta_N \eta\,[p(3-\sigma_N)+\sigma_N-1]}{2\alpha_{A_N}(1-\sigma_N)^2(\rho+\delta)} > \frac{\beta_N \eta\,[1-\sigma_N+\sigma_N-1]}{2\mu_{A_N}(1-\sigma_N)^2(\rho+\delta)} = 0, \quad \frac{1}{3} < p < 1$$

$$E_N^s - E_N^{\mathrm{n}} = \frac{\chi_N \mu\,[p(3-\theta_N)+\theta_N-1]}{2\alpha_{A_N}(1-\omega_N)^2(\rho+\varepsilon)} > \frac{\chi_N \mu\,[1-\sigma_N+\sigma_N-1]}{2\mu_{A_N}(1-\omega_N)^2(\rho+\varepsilon)} = 0, \quad \frac{1}{3} < p < 1.$$

Corollary 1: In the case of integrated decision making, core enterprises and satellite enterprises make the largest effort in knowledge innovation research and development and fulfill environmental social responsibility, and the optimal return is higher than the other two modes.

Corollary 2: when the profit ratio of core enterprises is $\left(0, \frac{1}{3}\right)$, the efforts of satellite enterprises are the same under the three game decisions. When the profit ratio of the core enterprise is $\left(\frac{1}{3}, 1\right)$, the core enterprise will share the cost with the satellite enterprise, and the satellite enterprise will make more efforts in the Stackelberg master-slave game than in the decentralized decision.

Proposition 2: When the government subsidy rate of satellite enterprises is $\left(0, \frac{2}{3}\right)$, the core enterprises and satellite enterprises in the enterprise green innovation ecosystem tend to cooperate. However, when the government subsidy rate is $\left(\frac{2}{3}, 1\right)$, that is, the government excessively encourages enterprises to fulfill their environmental social responsibilities, which has a certain negative impact on their own knowledge innovation research and development and overall benefits. At this point, dual-agent enterprises adopt Nash non-cooperative game or Stackelberg master-slave game, but do not tend to cooperate. When $\frac{1}{3} < p < \frac{1-\sigma_N}{1+\sigma_N}$, under the centralized decision, the higher the subsidy rate of the government for satellite enterprises, the higher the enthusiasm of satellite enterprises, and the income of core enterprises increases indirectly. As a result, the income of both dual-subject enterprises increases, but the proportion of the income of core enterprises decreases. From the three decision proof processes, $p > \frac{1-\sigma_N}{1+\sigma_N}, D_N^s > D_N^c, T^s > T^c, S^s > S^c$; When $0 < p < \frac{1-\sigma_N}{1+\sigma_N}, D_N^s < D_N^c, T^s < T^c, S^s < S^c$.

Corollary 3: The higher the subsidy rate of government to satelliteenterprises is within a certain range, the higher the proportion of revenue of satellite enterprises is. However, when the subsidy rate is higher than a certain range, dual-agent enterprises are not inclined to collaborative in innovation.

Proposition 3: Under three decision-making scenarios, the comparative analysis results of the knowledge innovation R&D level and the fulfillment of environmental social responsibility of the innovation system of dual-agent enterprises are as follows: $T^c > T^s > T^n, S^c > S^s > S^n$.

Proof:

$$\frac{dT}{dK} = 1 - e^{-\delta t} > 0(\delta > 0), \quad \frac{dS}{dK} = 1 - e^{-\delta t} > 0(\delta > 0),$$

T and S are both increasing functions of K, so, $T^c > T^s > T^n, S^c > S^s > S^n$.

Corollary 4: Sharing a certain proportion of cost by the core enterprise to the satellite enterprise can improve the overall revenue of the multi-agent enterprise cooperative innovation system. Under centralized decision-making, as the core enterprises and satellite enterprises make the largest efforts in knowledge innovation R&D and they fulfill environmental social responsibility, the multi-agent enterprises in the green innovation ecosystem achieve the highest level of knowledge innovation R&D and they fulfill environmental social responsibility income.

Proposition 4: Under three decision scenarios, the comparative analysis results of optimal returns of core enterprises and satellite enterprises and overall returns of multi-agent enterprise innovation system of enterprise green innovation ecosystem are as follows: $V^c > V^s > V^n, V_M^s > V_M^n, V_N^s > V_N^n$.

Proof:

$$V_M^s - V_M^n = \frac{\beta_N^2 \eta^2 [2p - (1-p)(1-\sigma_N)]^2}{8\rho\alpha_{D_N}(1-\sigma_N)^2(\rho+\delta)^2} + \frac{\chi_N^2 \mu^2 [2p - (1-p)(1-\omega_N)]^2}{8\rho\alpha_{E_N}(1-\omega_N)^2(\rho+\varepsilon)^2} > 0$$

$$V_N^s - V_N^n = \frac{(1-p)^2 \beta_N^2 \eta^2}{4\rho\alpha_{D_N}(1-\sigma_N)^2(\rho+\delta)^2} + \frac{(1-p)^2 \chi_N^2 \mu^2}{4\rho\alpha_{E_N}(1-\omega_N)^2(\rho+\varepsilon)^2} > 0$$

Combining proposition 1, when $\frac{1}{3} < p < \frac{1-\sigma_N}{1+\sigma_N}$, $T^c > T^S, S^c > S^S$, so $V^c - V^s$, as shown at the bottom of the page.

Corollary 5: In Stackelberg master-slave game, the optimal returns of core firms and satellite firms and the overall returns of multi-agent firms' cooperative knowledge innovation system are both higher than the corresponding values in Nash non-cooperative game, which is Pareto effective.

Corollary 6: Under centralized decision making, the overall benefit of multi-agent enterprise knowledge innovation system is the highest and is Pareto optimal.

V. CASE ANALYSIS

It can be seen from the above three decision-making situations that the optimal strategy, optimal income, knowledge innovation R&D system and additional income brought by the fulfillment of environmental social responsibility of the core enterprise and satellite enterprise respectively depend on the parameter setting in the model. Referring to [50] and combining with the actual situation, set $\alpha_{D_M} = 0.45$, $\alpha_{D_N} = 0.25, \alpha_{E_M} = 0.35, \alpha_{E_N} = 0.15, \beta_M = 0.5, \beta_N = 0.3, \chi_M = 0.3, \chi_N = 0.2, \sigma_M = 0.4, \sigma_N = 0.4, \omega_M = 0.3, \omega_N = 0.3, \eta = 5, \mu = 4, \delta = 0.2, \varepsilon = 0.1, \pi_0 = 10, \rho = 0.1, p = 0.7, T_0 = 8, S_0 = 4, t = 1$.

By substituting the parameters into theorems 1, 2 and 3, the solution is obtained: $D_M^c = 30.86, D_M^n = 38.88, D_M^s = 21.6, E_M^c = 31.17, E_M^n = 17.14, E_M^s = 17.14, D_N^c = 33.33, D_N^n = 10, D_N^s = 43.89, E_N^c = 38.1, E_N^n = 11.42, E_N^s = 29.2, T^c = 29.6, T^n = 19, T^s = 28.16, S^c = 16.27, S^n = 10.38, S^s = 16.27, V_M^n = 2096.86, V_M^s = 3188.44, V_N^n = 1179.24, V_N^s = 1228.36, V^c = 4566.52, V^n = 3275.93, V^s = 4416.8$. That satisfies proposition 1 to 4.

By substituting the solution results into three decision-making situations, we can get: in centralized decision-making $T^c = 127.16 - 119.16e^{-0.2t}, S^c = 149.66 - 145.66e^{-0.1t}, V^c = 16.67T+20S+3715.89$; in decentralized decision making $T^n = 69.01 - 61.01e^{-0.2t}, S^n = 139.03 - 135.03e^{-0.1t}, V_M^n = 11.67T + 14S + 2632.03, V_N^n = 5T + 6S + 1021.96, V^n = 16.67T + 20S + 3043.69$; in the Stackelberg master-slave game, $T^s = 119.84 - 111.84e^{-0.2t}, S^s = 139.03 - 135.03e^{-0.1t}, V_M^s = 11.67T + 14S + 2632.03, V_N^s = 5T + 6S + 989.94, V^s = 16.67T + 20S + 3621.97$. As shown in the Fig. 2-10.

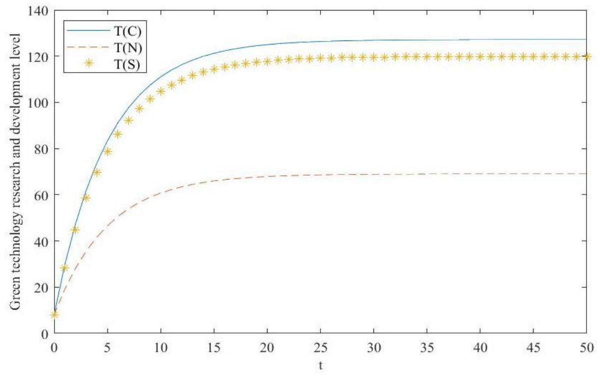

FIGURE 2. Comparison of innovation system R&D level trend.

It can be concluded from Fig. 2-3 that, as the core subject of the enterprise green innovation ecosystem, the knowledge innovation level and social environmental responsibility effect of the knowledge innovation system composed of core enterprises and satellite enterprises keep a positive correlation with time and eventually stabilize. By sharing costs with satellite enterprises, core enterprises can improve the enthusiasm of satellite enterprises, and directly enhance the knowledge innovation research and development level of innovation system and social environmental responsibility effect. In the three decision-making situations, the optimal returns of both parties reach the highest in the centralized

$$\begin{aligned}
V^c - V^s = {} & \frac{\eta}{\rho+\delta}\left(T^c - T^s\right) + \frac{\mu}{\rho+\varepsilon}\left(S^c - S^s\right) + \frac{\beta_M^2\eta^2}{2\rho\alpha_{D_M}\left(1-\sigma_M\right)\left(\rho+\delta\right)^2} - \frac{p\left(2-p\right)\beta_M^2\eta^2}{2\rho\alpha_{D_M}\left(1-\sigma_M\right)\left(\rho+\delta\right)^2} \\
& + \frac{\beta_n^2\eta^2}{2\rho\alpha_{D_N}\left(1-\sigma_N\right)\left(\rho+\delta\right)^2} - \frac{\left[4p^2 + 4p\left(1-p\right)\left(1-\sigma_N\right) + \left(1-p\right)^2\left(1-\sigma_N\right)^2 + 2\left(1-p\right)^2\right]\beta_N^2\eta^2}{8\rho\mu_{D_N}\left(1-k_N\right)^2\left(\rho+\delta\right)^2} \\
& + \frac{\chi_M^2\mu^2}{2\rho\alpha_{E_M}\left(1-\omega_M\right)\left(\rho+\varepsilon\right)^2} - \frac{p\left(2-p\right)\chi_M^2\mu^2}{2\rho\alpha_{E_M}\left(1-\omega_M\right)\left(\rho+\varepsilon\right)^2} + \frac{\chi_N^2\mu^2}{2\rho\alpha_{E_N}\left(1-\omega_N\right)\left(\rho+\varepsilon\right)^2} \\
& - \frac{\left[4p^2 + 4p\left(1-p\right)\left(1-\omega_N\right) + \left(1-p\right)^2\left(1-\omega_N\right)^2 + 2\left(1-p\right)^2\right]\chi_N^2\mu^2}{8\rho\alpha_{E_N}\left(1-\omega_N\right)^2\left(\rho+\varepsilon\right)^2} \\
> {} & \frac{\eta}{\rho+\delta}\left(T^c - T^s\right) + \frac{\mu}{\rho+\varepsilon}\left(S^c - S^s\right) + \frac{\chi_M^2\eta^2}{2\rho\alpha_{D_M}\left(1-\sigma_M\right)\left(\rho+\delta\right)^2} - \frac{p\left(2-p\right)\chi_M^2\eta^2}{2\rho\alpha_{D_M}\left(1-\sigma_M\right)\left(\rho+\delta\right)^2} \\
& + \frac{\chi_N^2\mu^2}{2\rho\alpha_{D_N}\left(1-\sigma_N\right)\left(\rho+\delta\right)^2} - \frac{11p^2\chi_N^2\mu^2}{8\rho\alpha_{D_N}\left(1-\sigma_N\right)^2\left(\rho+\delta\right)^2} + \frac{\chi_M^2\mu^2}{2\rho\alpha_{E_M}\left(1-\omega_M\right)\left(\rho+\varepsilon\right)^2} \\
& - \frac{p\left(2-p\right)\chi_M^2\mu^2}{2\rho\alpha_{E_M}\left(1-\omega_M\right)\left(\rho+\varepsilon\right)^2} + \frac{\chi_N^2\mu^2}{2\rho\alpha_{E_N}\left(1-\omega_N\right)\left(\rho+\varepsilon\right)^2} \\
& - \frac{11p^2\chi_N^2\mu^2}{8\rho\alpha_{E_N}\left(1-\omega_N\right)^2\left(\rho+\varepsilon\right)^2} \\
> {} & 0
\end{aligned}$$

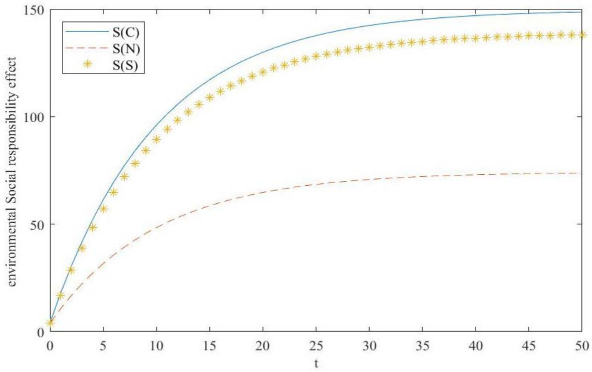

FIGURE 3. Comparison of the effect trend of R&D innovation system to fulfill environmental social responsibility.

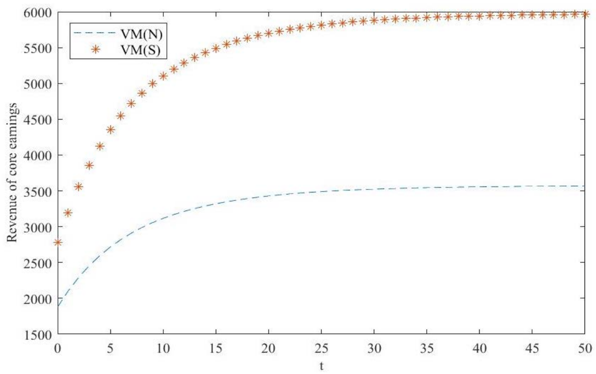

FIGURE 4. Comparative analysis of core enterprise income.

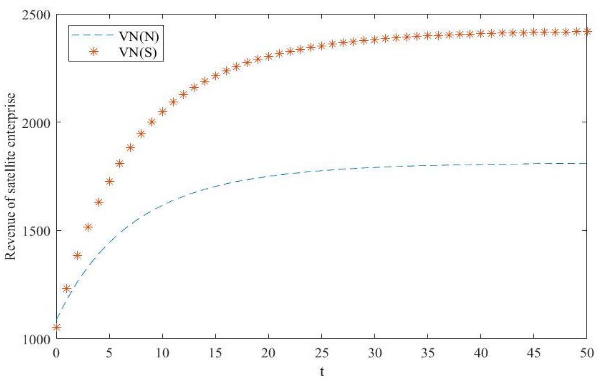

FIGURE 5. Comparative analysis of satellite enterprise income.

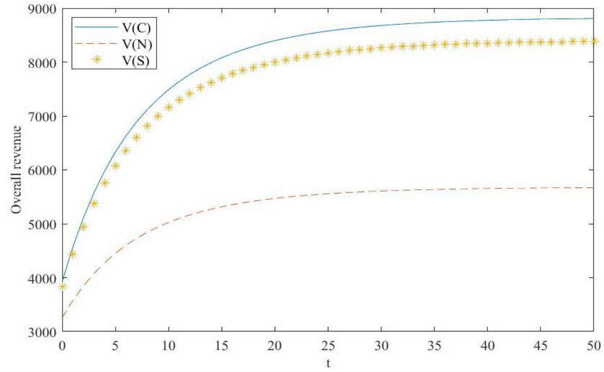

FIGURE 6. The trend comparison of overall revenue of R&D innovation system.

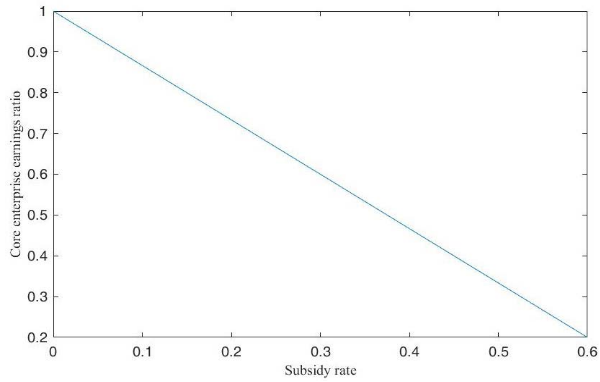

FIGURE 7. The influence of government subsidies to satellite enterprises on the income share of core enterprises.

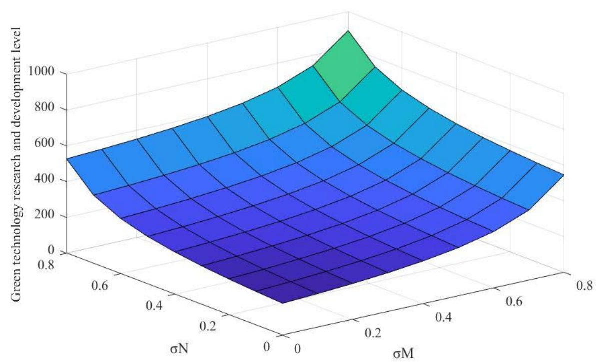

FIGURE 8. The influence of government subsidies to R&D innovation system on knowledge innovation.

decision, followed by the Stackelberg master-slave game, and the lowest in the decentralized decision, that is, $T^c > T^s > T^n, S^c > S^s > S^n$, which is consistent with proposition 3.

It can be concluded from Fig. 4-5 that the optimal returns of both core enterprises and satellite enterprises are positively correlated with time and tend to be stable after reaching equilibrium. The core enterprises share costs with satellite enterprises, which significantly promotes the increase of revenue of both parties, that is, $V_M^s > V_M^n$, $V_N^s > V_N^n$. As can be seen from Fig. 6, in the knowledge innovation R&D system composed of dual-agent enterprises, the overall income also shows a positive correlation with time, and then tends to be stable, and the overall income is the highest under centralized decision, that is, $V^c > V^s > V^n$, which is consistent with proposition 4. Figure 7 shows that with the continuous increase of government subsidy rate to satellite enterprises, the total income of the Knowledge

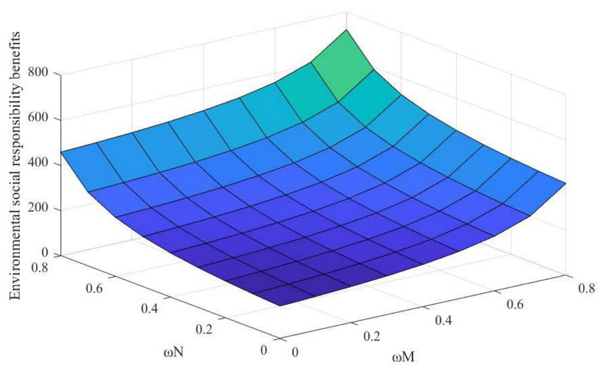

FIGURE 9. The impact of government incentives for R&D innovation system to fulfill environmental and social responsibilities on social and environmental effects.

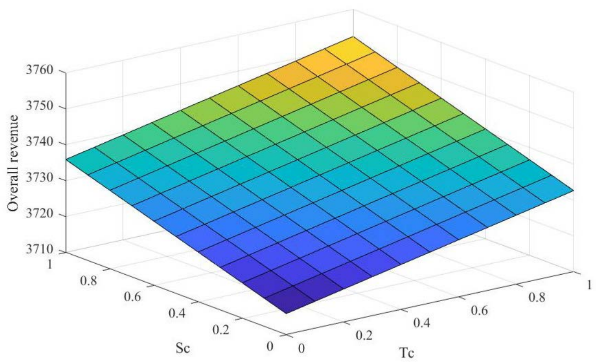

FIGURE 10. The influence of knowledge innovation level and environmental social responsibility effect on total revenue of R&D system.

innovation R&D system increases, but the proportion of income of core enterprises decreases, which is consistent with proposition 2.

Figure 8-10 reflects the influence of government subsidies and rewards on the main parameters of collaborative green technology R&D system under centralized decision making.

Figures 8 and 9 show that the technical level of the knowledge innovation R&D system of collaborative innovation constructed by core enterprises and satellite enterprises is positively correlated with government subsidies and rewards. Within a reasonable range, the higher the government subsidies and incentives for R&D innovation system, the higher the increase in the technological level and social environmental effects of R&D innovation system. It can be seen from Fig. 10 that the knowledge innovation level and social environment of R&D innovation system together improve the overall income. This shows that, in order to accelerate the completion of the ''dual carbon'' strategic goal, the government's active guidance to enterprises not only promotes enterprises to improve their knowledge innovation level, but also strengthens their motivation to fulfill their environmental social responsibility. After receiving government subsidies and rewards, enterprises will give full play to the advantages of the ecosystem, actively obtain cutting-edge information and high-quality resources from the outside world, and constantly improve the green innovation level of the knowledge innovation R&D system. In addition, with the gradual enhancement of environmental social effects, enterprises will pay more attention to their own virtuous image and reputation, and constantly enhance the initiative to fulfill environmental social responsibility, so as to form a virtuous circle of technological level and environmental social effects of knowledge innovation research and development system.

VI. CONCLUSION AND IMPLICATIONS

From the perspective of innovation ecosystem, this paper conducts research based on core competency theory, resource-based theory, symbiotic evolution, game theory, etc., embeds the theory of corporate environmental social responsibility into the knowledge innovation R&D system constructed by multi-agent enterprises in the ecosystem, and uses the differential game method. The paper analyzes the benefits of knowledge innovation, R&D innovation and fulfillment of environmental and social responsibilities of core enterprises and satellite enterprises. Taking into account the effects of knowledge innovation, R&D innovation and environmental social responsibility effects, companies may face the ''innovation paradox'', which will have a negative impact on the overall revenue of the entire R&D system. The green innovation ecosystem of enterprises is dominated by core enterprises and coordinated by multiple entities, forming a situation of symbiotic evolution and win-win cooperation under limited resources. After incorporating environmental and social responsibility into the green technology R&D system, the ecosystem has more uncertain factors, and achieving a balance between improving knowledge innovation, R&D innovation capabilities and fulfilling environmental social responsibility has become an important decision-making issue for main enterprises. This paper constructs a dynamic decision-making problem under three situations of centralized decision-making, decentralized decision-making and Stackelberg master-slave R&D led by core enterprises, and conducts a comprehensive comparative analysis, and then it conducts simulation analysis to obtain the following conclusions:

First, collaborative innovation of knowledge innovation R&D system under centralized decision making is the optimal path for multi-agent enterprises to improve knowledge innovation level and sustainable development. Core enterprises and satellite enterprises share resources and complement each other in information, and actively participate in knowledge innovation research and development, thus enhancing the momentum and vitality of the ecosystem. In the process of improving the level of knowledge innovation, enterprises actively fulfilling environmental social responsibility will strengthen their virtuous image and reputation, which in turn increases the convenience of obtaining high-quality resources. Therefore, enterprises can continue to maintain a healthy development trend, actively maintain the network relationship in the ecosystem, carry other subjects for knowledge innovation research and development, and finally achieve symbiotic development.

Second, the optimal benefits of core enterprises and satellite enterprises and the overall benefits of the knowledge innovation R&D system under decentralized decision-making are the lowest, but the optimal collaboration method for multi-agent R&D system in the ecosystem is not achieved. Collaboration between core enterprises and satellite enterprises to realize the coupling and balance of green technology research and development and environmental social responsibility is the cornerstone of the ecosystem. Under the constraints of the strategic goal of "carbon peaking and carbon neutrality", enterprises are facing the pressure of multiple knowledge innovation research and development and building an innovation ecosystem development model; a model that has become an inevitable choice. The higher the government's subsidy for knowledge innovation and R&D of satellite enterprises, the higher the proportion of revenue obtained by satellite enterprises. Although the proportion of core enterprises' income decreases, it does not harm the interests of the green technology research and development system. This shows that there is a marginal increase in the additional benefits generated by centralized decision-making in the knowledge innovation R&D system, and the benefits generated by the same cost and resources are higher than those generated by decentralized decision-making. Therefore, core enterprises should give full play to their leading and guiding roles, establish an efficient collaborative cooperation model with satellite enterprises, and jointly improve the level of knowledge innovation research and development in the ecosystem, and the government should adopt reasonable subsidies to increase the enthusiasm of the research and development system.

Third, the government, as an important main body of the green innovation ecosystem of enterprises, provides necessary subsidies and support for enterprises to improve their knowledge innovation R&D level and fulfill their environmental and social responsibilities. This incentive behavior significantly increases the enthusiasm of enterprises to participate and promote the ecosystem, which achieves the key goal of symbiotic evolution. Based on the decision-making model and simulation results, it is found that the knowledge innovation R&D system composed of core enterprises and satellite enterprises has the highest degree of effort in technological innovation and fulfilling environmental social responsibility under the centralized decision-making situation. Within a reasonable level of effort, the performance of environmental social responsibility by enterprises can positively promote the balance of the knowledge innovation R&D system, and at the same time promote the knowledge innovation R&D system to achieve optimal returns and Pareto optimality. However, when the ecosystem is out of balance, the excessive support of core enterprises will directly lead to the "free-rider" behavior of satellite enterprises. At this time, the income of the knowledge innovation R&D system increases significantly, but the income of core enterprises does not reach one-third of the overall income, which reflects the phenomenon of "innovation paradox" of core enterprises. When the government subsidizes satellite enterprises excessively, it boosts the parasitic innovation of satellite enterprises. At this time, the knowledge innovation R&D system changes from Stackelberg's master-slave innovation to parasitic innovation, and it is difficult for the green innovation ecosystem of enterprises to maintain a healthy development trend. Therefore, the government should actively guide the core enterprises, give appropriate subsidies to the green technology research and development system, and promote the construction and healthy development of the green innovation ecosystem.

VII. RESEARCH LIMITATIONS AND PROSPECTS

The innovation ecosystem and environmental social responsibility involve a wide range of disciplines. This paper only takes the green innovation ecosystem as the research object and uses differential games to analyze the innovation mode and influencing factors of the knowledge innovation R&D system. In future research work, other subjects such as financial institutions and upstream and downstream enterprises should be included in the decision-making process for analysis. In addition, more variables should be added to the decision-making model, in order to deeply analyze the knowledge innovation R&D system from different perspectives, and to further analyze the optimal equilibrium state of the ecosystem.

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