Pol. J. Environ. Stud. Polit. Econ. Ind. Vol. XX, No. X (XXXX), 1-23
DOI: *10.15244/peai/205067* ONLINE PUBLICATION DATE:

Original Research

Research on Collaborative Governance Decision-Making for Data Security in Innovation Ecosystem under the Metaverse

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Received: 8 March 2025
Accepted: 12 May 2025

Abstract

With the rapid development of metaverse technology, data security governance within its innovation ecosystem has become a critical challenge. This study explores data security collaborative governance decision-making aimed at maximizing energy efficiency and minimizing environmental impact throughout the data lifecycle. It proposes an innovative model for synergistic data security governance and green sustainability, constructing an efficient, secure, and sustainable governance framework. This provides theoretical support and practical guidance for the long-term healthy development of the metaverse ecosystem. Against the backdrop of the metaverse, this paper constructs three game models – Nash non-cooperative, Stackelberg leader-follower, and collaborative cooperative – based on complex systems theory, collaborative governance theory, and differential game theory. From a dynamic perspective, it examines the data security collaborative governance decision-making issues among three key entities: core enterprises, research institutions, and the government. Finally, numerical simulation analysis is conducted. The research findings reveal the following: (1) Government policy support and innovation subsidies can enhance the willingness of core enterprises and research institutions to engage in collaborative governance. Under government incentives and subsidies, the optimal benefits for participating entities and the overall benefits of the ecosystem are improved. (2) The three game mechanisms have heterogeneous effects on improving collaborative governance levels. When the initial level of collaborative governance is low, all three mechanisms can drive its improvement. As the level of collaborative governance increases, the leader-follower game under government incentives promotes better collaborative governance outcomes in the innovation ecosystem. When the level of collaborative governance is very high, only the collaborative cooperation mechanism can further enhance it. (3) Strategies in the cooperative game not only involve optimal decision analysis but also emphasize the promotion of ecosystem integration and optimization through synergistic mechanisms to achieve whole-process, dynamic data security governance, while promoting efficient resource utilization

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and environmental sustainability, and building a synergistic governance model between data security and green development.

Keywords: metaverse, innovation ecosystem, collaborative data security governance, differential game, green development

Introduction

The Metaverse is considered the third wave of the Internet revolution, and it is built on new and emerging technologies such as extended reality and artificial intelligence [1]. Metaverse, as a new industrial domain eagerly explored by numerous tech giants, offers people novel experiences due to its characteristics of decentralization, high immersion, and strong interactivity. However, the development of the metaverse also faces numerous challenges in areas such as privacy, trust, and security [2]. At the same time, the energy-intensive nature of the metaverse poses a serious challenge to global green sustainability goals. Numerous companies are utilizing metaverse technologies while paying more attention to data security privacy protection, and green sustainability. For example, Microsoft integrates metaverse technology into office scenarios through Mesh for Teams, employing multi-layered data encryption and access control mechanisms. Its data centers utilize renewable energy and optimize energy efficiency through AI. Meta collects vast amounts of user data on metaverse platforms such as Horizon Worlds, enhancing the encryption and anonymization of user data, while also reducing the energy consumption of computing resources through algorithm optimization. The operation of the metaverse relies on large-scale data centers and computing resources, with its energy consumption and carbon emissions growing exponentially. By integrating green technologies with data security governance, the dual goals of sustainability and security can be achieved. Therefore, based on differential game theory, complex systems theory, and collaborative governance theory, this paper considers the incentivizing role of the government to study the decision-making issues of collaborative data security governance in the innovation ecosystem within the metaverse. This research contributes to enriching the mechanisms of multi-agent collaborative data security governance, provides important theoretical insights for the safe and stable development of the metaverse ecosystem and the governance decisions of innovation entities, advances the field of differential game research in multi-agent collaborative data security governance, and holds significant implications for promoting future societal technological development and constructing an efficient, secure, and environmentally friendly metaverse ecosystem.

Although existing research has explored multiple dimensions of the metaverse, including its characteristics [3, 4], technological applications [5, 6], enabling mechanisms [7, 8], and security challenges during its development [9], and has achieved certain results, studies on the construction of the metaverse innovation ecosystem and data security governance – particularly the exploration of effective collaborative governance mechanisms and strategies under government incentives – remain relatively underdeveloped. The academic community recognizes that research on innovation ecosystems holds profound multidimensional significance and irreplaceable strategic value. Scholars have systematically reviewed the structure [10], constituents [11], evolutionary pathways [12], and governance mechanisms of innovation ecosystems [13, 14], analyzing the interdependent and synergistic relationships among their constituent elements. They have also investigated the operational dynamics of core processes, such as interactions and feedback among innovation entities, and focused on establishing effective collaborative governance mechanisms to balance the interests of all stakeholders. These efforts provide a clear theoretical foundation and research direction for this study. Based on the theoretical foundations of previous scholars, this paper addresses the following research questions: How can the government integrate green policy tools with the data security governance framework, enhance the willingness of core enterprises and scientific research institutions to collaborate in governance through a dynamic reward and punishment mechanism, and drive the formation of a low-carbon collaborative symbiosis model? In data security governance, how can enterprises reduce the cost of security inputs through green technology innovation, build a dual-objective optimization model of "security-energy efficiency", and achieve a sustainable balance between data security governance and economic benefits? How do firms' technological innovation and data security risk assessment capabilities affect the dynamic evolutionary process of optimal returns over time in a synergistic symbiosis system? How should governments, core enterprises, and research institutions dynamically adjust their decision-making strategies to enhance the efficiency of data security governance and safeguard the sustainable resilience of the innovation ecosystem in a green development-oriented multi-dimensional synergy model?

The innovations of this paper are mainly as follows: (1) Previous studies have focused on the macro context of big data and digital transformation to analyze data security governance issues. However, this paper innovatively anchors the viewpoint in the emerging environment of the metaverse to conduct an in-depth study on the collaborative governance of data security by multiple actors. (2) While previous research focuses more on data security governance within the scope of a single subject of an enterprise or a government, this study breaks through the limitations and focuses on exploring the multifaceted elements and their complex associations involved in collaborative data security governance from the macro level of the system as a whole. (3) Previous scholars have more often chosen the literature study or case study method to research data security governance issues. In this paper, we choose the differential game method to dynamically capture the changes in decision-making and mutual influences of the subjects' collaborative governance at different points in time, which is more in line with the dynamics and complexity of the data security problem in the metaverse environment. (4) Considered the impact of government incentive policies on the willingness of core companies and research institutions to engage in collaborative governance, and derived the optimal incentive coefficient for the government, providing a specific quantitative basis for the government to formulate effective incentive policies to improve the overall data security collaborative governance level of the system. (5) The study innovatively integrates data security governance with the concept of green development. In existing research, data security governance has predominantly focused on traditional aspects, with scant attention paid to its potential connections with green development. This research breaks down the barriers among participating entities in traditional data security governance, emphasizing collaborative cooperation among all stakeholders under the guidance of green development objectives.

Relevant Concepts and Theoretical Foundations

Definition of Relevant Concepts

The Concept of the Metaverse

Different people have their unique understanding of the metaverse from different perspectives, and thus, there is still no consensus on the concept of the metaverse. Some scholars define the metaverse as a fully immersive, three-dimensional virtual world that is parallel to the physical world [15, 16]. Kim considered the metaverse as an interoperable persistent network, where people can share the virtual environment of the metaverse and interact with other objects in real time [17]. Schöbel et al. considers that the metaverse is a massively scaled and interoperable meta-ecosystem of other digital ecosystems of real-time rendered 3D virtual worlds, which can be experienced synchronously and persistently by an unlimited number of complementors and consumers with an increased user experience caused by a creativity-guided co-creation of goods managed by orchestrators and supported by platform owners [18]. This paper argues that the metaverse is a new type of social ecosystem that integrates and interacts with the virtual and the real, consisting of complete and stable operation of technology, content, economy, collaboration, and governance subsystems, and characterized by a high degree of immersion, real-time permanence, autonomous creation, and openness and interconnectivity.

The Concept of the Innovation Ecosystem

Granstrand et al. consider that the innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors [19]. Some scholars argue that the innovation ecosystem is composed of different stakeholders, including industry players, the government, associations, customers, and others who inhabit the same scenario and coevolve with each other, appropriating new values through innovation [20]. Guo et al. point out that the innovation ecosystem consists of core layer subjects, such as enterprises, universities, and R&D organizations, peripheral layer subjects, such as the government and the public, as well as innovation platforms and innovation infrastructure [21]. Scholars have defined the innovation ecosystem from different perspectives and have developed a systematic discussion. Based on this, this paper considers that the innovation ecosystem is a win-win, high-efficiency collaboration and resource-sharing innovation network jointly constructed by internal subjects and external subjects in a certain innovation environment through coordinating and integrating innovation resources and building an innovation platform, in which the internal subjects include core subjects such as enterprises, colleges and universities, research organization, and the government, and the external subjects include auxiliary subjects such as financial institutions and intermediary organizations.

The Concept of Collaborative Governance

Su et al. argue that collaborative governance will effectively motivate government agencies, industry associations, operators, consumers, and other stakeholders to improve the overall efficiency of governance by promoting collaborative efforts in the governance process. Its core principle is to achieve governance objectives through multi-party participation, resource sharing, and the distribution of power and responsibility [22]. Ding et al. argue that polycentric collaborative governance is composed of government, business, society, and the public, and that it is the key force in enhancing the resilience of the security ecology [23]. Nicola et al. believe that collaborative governance involves different participants interactively engaging in solving common problems, challenges, and opportunities. Collaborative governance is essentially understood as a process in which participants work together or collaborate [24]. Based on this, this paper defines the concept of collaborative governance as an institutionalized collective decision-making process between two or more subjects, which forms an efficient cooperation mechanism and interaction mode and creates common value by integrating the resources of multiple subjects.

Theoretical Foundations

Complex Systems Theory

In the 1940s, Bertalanffy's "general system theory" became the symbol of the emergence of complex system theory [25]. In the 1970s, Belgian scholar Prigogine put forward the concept of dissipative structure [26], German scholar Haken put forward synergism [27], and Eigen put forward the theory of super-cycle, enriched Bertalanffy's "general system theory", and upgraded the system theory by one level. Later, many scholars researched this basis, resulting in operations research, systems theory, and the theory of complex adaptive systems proposed by Holland in the 1980s [28], and nonlinear science has become an international academic research hotspot. A complex system is a system consisting of a large number of interacting and interdependent components with unpredictable system behavior. These components can be simple or complex, and their interactions and dependencies are highly complex, thus making it difficult to accurately predict and understand the characteristics, behaviors, and properties exhibited by the system as a whole. Yang argues that there are complex interactions between system elements in complex systems, and that systems exhibit complex characteristics such as emergence, self-organization, uncertainty, and dynamics at the macro scales [29]. Domenech argues that the operation of a complex system depends on its structure, and the chronology of changes at each level of the complex system determines its behavior. Environment, structure, function, and behavior constitute the complex system-environment unit, which is the operational unit in which all open complex systems exist [30]. The tools of complex systems theory provide new perspectives for analyzing and interpreting data from real systems [31]. Complex systems theory is widely used in the field of management. This study involves multiple elements, and the interaction and cooperation between the subjects may generate emergent phenomena. The use of complex systems theory can help to identify these elements and their interrelationships, and to guide and promote the occurrence of these benign emergences. It also supports the study of the system's overall behavior and characteristics, providing a basis for decision-making in the collaborative governance of data security.

Collaborative Governance Theory

Synergy theory studies how an open system far from equilibrium can form an orderly structure in time, space, and function through internal synergistic effects when it exchanges material or energy with the outside world. Synergy theory reveals the common law of the transition from disorder to order in all kinds of systems and phenomena, and its universality provides new perspectives and methods for people to study the evolution law of complex systems in the social or natural world, macro or micro [32]. The most central concept of synergistic governance is synergy and cooperation [33], which effectively combines governance theory and synergistic ideas, and it is capable of solving complex public governance problems, with the important goal of achieving good governance and synergistic efficiency gains. In the context of public management, collaborative governance is a governance process in which one or more public sectors make decisions and implement them directly with non-governmental organizations with a stake in the process [34]. Collaborative governance theory is the core theory of the whole research process of this paper, based on this theory, this paper constructs a collaborative governance framework of multiple subjects, integrates the resources and expertise of each governance subject, comprehensively assesses and dynamically monitors the data security risks in the metaverse innovation ecosystem, and proposes a collaborative governance decision-making process for data security.

Differential Game Theory

In the field of differential games, most of the initial research results used optimal control theory to solve differential game problems [35]. In 1957, Bellman proposed dynamic programming [36], and in 1958, Pontryagin proposed the principle of great value, and the proposal of these two theories strongly supported the formation and development of optimal control theory [37]. Differential games, also known as differential countermeasures, originated in the study of two-party pursuit problems in military demand confrontations. The earliest research on the problem of fugitive pursuit, in which both adversaries are free to decide and act, was led by Dr. Isaacs, an American mathematician, using modern control theory. Differential countermeasures are an important class of dynamic countermeasure models, a deep integration of optimal control theory and game theory, used to study the evolution of phenomena or laws in a system in continuous time, using differential Equations to describe the state of a dynamic system at any moment during the game. Differential games are widely used in various fields of social life and economic management and have become a scientific and effective decision-making tool. Differential game theory runs through the entire research work of this paper, providing key guidance from model construction and simulation analysis of algorithms.

Problem Description and Model Assumptions

Problem Description

In the metaverse innovation ecosystem, core enterprises, research institutions, and the government each play an important role and are interdependent. As the core carrier of technology implementation and resource integration, core enterprises dominate the construction and operation of virtual space infrastructure. Research institutes break through the traditional energy-consuming governance model through green technology innovation, and promote the synergistic realization of data security and low-carbon goals. The government builds an institutional framework that balances security and environmental protection through green policy provision and cross-domain regulatory coordination. The closed loop of "technology iteration, innovation drive, institutional constraints" formed by the three parties can systematically solve the dual challenges of data security governance and green development in the metaverse. Therefore, under the background of the metaverse, it is necessary to study the issue of collaborative data security governance among core enterprises, scientific research institutions, and the government in the innovation ecosystem. In this system, core enterprises in the metaverse act as the facilitators of data security governance, while scientific research institutions provide them with innovation resources and carry out data security technology research and development under the government's supervision and incentives. Core enterprises provide research institutions with practical platforms and financial support for data security research, the government regulates and incentivizes them, and research institutions provide technical and intellectual support for data security governance as an innovation source. Scientific research institutions provide decision-making advice and technical support for the government, core enterprises provide feedback to the government on data security needs, and the government provides policy support for the data safety governance process based on the recommendations of scientific research institutions and the needs of core firms. Through collaborative governance of data security, a stable environment for innovation is provided to ensure the sustainable development of the ecosystem. Based on the metaverse innovation ecosystem, the collaborative data security governance structure of the core enterprises, research institutes, and the government as a tripartite body is shown in Fig. 1.

Basic Assumptions

Exploring the data security collaborative governance strategies for core enterprises, research institutions, and the government to maximize their respective benefits and the total revenue of the innovation ecosystem under three scenarios: Nash non-cooperative games, Stackelberg leader-follower games, and cooperative games. The model parameters and meanings are shown in Table 1.

The following research hypotheses are formulated based on relevant research as well as modeling needs [38]:

(1) Core enterprises, scientific research institutions, and the government are completely rational, all pursuing the maximization of their interests and possessing complete information.

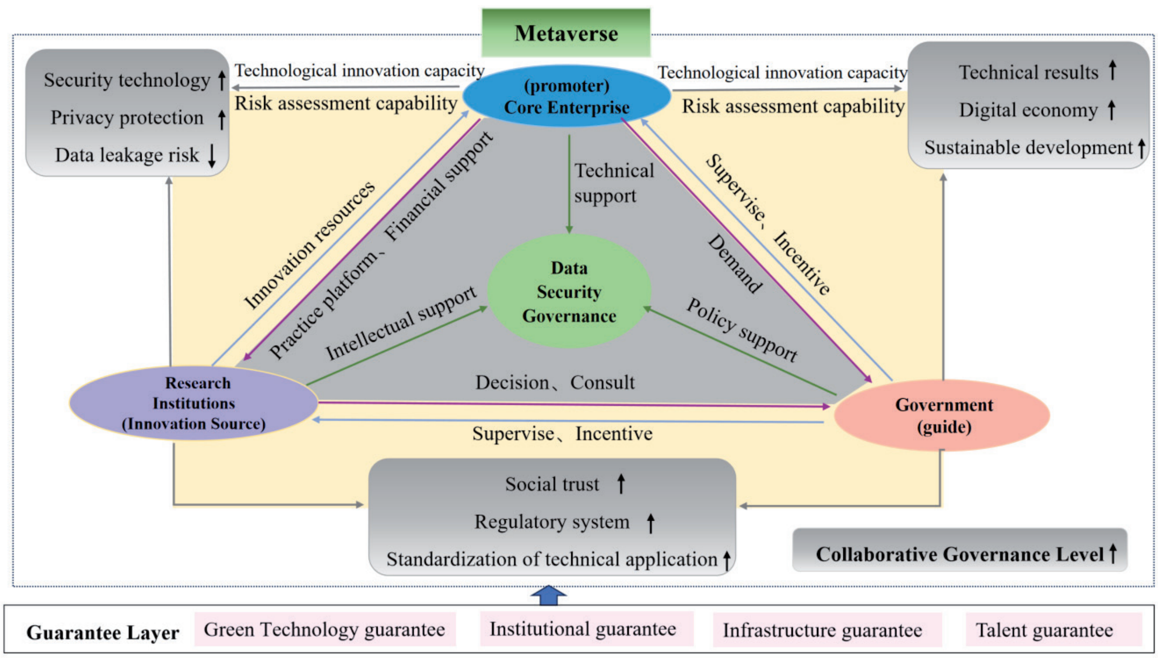


Fig. 1. Collaborative governance structure for data security in metaverse innovation ecosystems.

Table 1. Variable symbols and meanings.

Symbols	Meanings
R	Core enterprise.
E	Scientific research institution.
N	Government.
$B_i(t)$	The degree of collaborative governance efforts in data security, $i = R, E, N$.
λ_i	Cost coefficient of collaborative governance for data security, $i = R, E, N$.
g_R	Coefficient of technological innovation capability of core enterprises.
ω_R	Data security risk assessment capability coefficient for core businesses.
$C_i(t)$	Cost of collaborative governance for data security, $i = R, E, N$.
$I(t)$	Level of collaborative governance for data security.
θ_i	Coefficient of the impact of the level of data safety collaborative governance efforts on the level of collaborative governance, $i = R, E, N$.
ε	Decay rate of willingness to collaborate.
$\pi(t)$	The overall benefits of the innovation ecosystem at time t.
μ_i	Coefficient of the impact of the degree of effort on total return, $i = R, E, N$.
η	Coefficient of the impact of the level of collaborative data security governance on total benefits.
α	The profit distribution coefficient of core enterprises.
β	Revenue distribution coefficient for research institutions.
$1-\alpha-\beta$	Government revenue distribution coefficient.
γ	Government incentive coefficients for core enterprises.
δ	Government incentive coefficients for scientific research institutions.
ρ	Discount rate at any point in time.

(2) To maintain stability, security, and green sustainable development of the innovation ecosystem environment, core enterprises and research institutions collaborate in joint research and development of data security and green low-carbon technologies by sharing data resources, thereby optimizing the energy efficiency and environmental impact of data resources while enhancing the level of data security governance. Data security governance is a dynamic process of change, and $I'(t)$ denotes the level of collaborative data security governance at time t, which is related to the degree of efforts of core enterprises, research institutions, and the government to participate in data security governance. Therefore, the dynamic change process of the level of collaborative data safety governance is:

$$I'(t) = \theta_R B_R(t) + \theta_E B_E(t) + \theta_N B_N(t) - \varepsilon I(t) \tag{1}$$

$I'(t) = \dfrac{dI(t)}{dt}$, where $I(0) = I_0 \geq 0$ denotes the level of data security governance at the initial point in time.

(3) Data, as a critical asset, constitutes the core competitiveness of enterprises and serves as a fundamental guarantee for the stable operation of

innovation ecosystems. Through the deep integration of data security governance and the concept of green sustainable development, the approach not only enhances system security and reliability but also optimizes energy consumption in data centers. This dual focus not only reduces system failures and interruptions caused by data security issues, thereby improving the overall stability of innovation ecosystems, but also drives the innovative application of green low-carbon technologies, facilitating the green transformation and sustainable growth of the economy. By mitigating environmental risks and operational costs for enterprises, it strengthens their competitiveness in the era of the green economy, creating dual benefits of economic value and ecological sustainability for society. Assume that the total benefit to the innovation ecosystem at the moment t is

$$\pi(t) = \pi_0 + \mu_R B_R(t) + \mu_E B_E(t) + \mu_N B_N(t) + \eta I(t) \tag{2}$$

(4) The cost of collaborative data security governance for core enterprises, research institutes, and the government is related to the level of effort of collaborative data security governance. The cost input is a convex function of their effort. The cost functions of core enterprises, research institutes, and government at the moment *t* are respectively:

$$C_R(t) = (\frac{\lambda_R}{2} + \frac{1}{g_R + \omega_R})B^2{}_R(t)$$
$$C_E(t) = \frac{\lambda_E}{2} B^2{}_E(t)$$
$$C_N(t) = \frac{\lambda_N}{2} B^2{}_N(t) \tag{3}$$

(5) To carry out data security governance more effectively and build a more stable and secure innovation ecosystem, the government will provide incentives for core companies and research organizations, with an incentive coefficient of γ, $\delta \in [0,1]$. In the benefit distribution, the core companies, research organizations, and the government can obtain the total system revenue of α, β and $1 - \alpha - \beta$, respectively. The core companies, research organizations, and the government have the same arbitrary moment discount rate ρ.

(6) The remaining parameters in the model, such as the control variable $B_R(t)$, $B_E(t)$, $B_N(t)$, $\gamma(t)$, $\delta(t)$, the state variables $I(t)$, and α, β, ρ, are all greater than or equal to zero and are time-independent constants.

(7) According to the aforementioned assumptions and concerning the optimal control theory of differential games, the objective functions of the three parties, namely, the core enterprise, scientific research institution, and the government, are obtained as follows:

$$J_R = \max_{B_R(t)\geq 0} \int_0^\infty e^{-\rho t}\left[\alpha\pi(t) - (1-\gamma(t))\left(\frac{\lambda_R}{2} + \frac{1}{g_R+\omega_R}\right)B_R^2(t)\right]dt \tag{4}$$

$$J_E = \max_{B_E(t)\geq 0} \int_0^\infty e^{-\rho t}\left[\beta\pi(t) - (1-\delta(t))\frac{\lambda_E}{2}B_E^2(t)\right]dt \tag{5}$$

$$J_N = \max_{B_N(t)\geq 0} \int_0^\infty e^{-\rho t}\left[(1-\alpha-\beta)\pi(t) - \frac{\lambda_N}{2}B_N^2(t) - \gamma(t)\left(\frac{\lambda_R}{2} + \frac{1}{g_R+\omega_R}\right)B_R^2(t) - \delta(t)\frac{\lambda_E}{2}B_E^2(t)\right]dt \tag{6}$$

Materials and Methods

Model Establishment and Solution

This paper considers the influence of the time factor on the benefits of synergy, investigates the synergistic governance strategies and optimal benefits of the three actors and the optimum benefits of the innovation ecosystem as a whole under three scenarios, and constructs the models as follows: (1) Nash non-cooperative game; (2) Stackelberg leader-follower game; (3) collaborative cooperative game. For the convenience of writing, the writing of variable t will be omitted in the following.

Nash Non-cooperative Game Model

In this game-theoretic scenario, core companies, research organizations, and the government simultaneously and independently decide their degree of participation, seeking to maximize their benefits. The government will not provide incentives for core companies and research organizations. The optimal combination of decision-making strategies of the three parties in the game is called the static feedback Nash equilibrium, and the Nash game can also be regarded as a Stackelberg game with no-cost subsidy incentives. The objective functions of core enterprises, research institutions, and the government are as in Equations (7) to (9).

$$J_R = \max_{B_R\geq 0} \int_0^\infty e^{-\rho t}\left[\alpha\left(\pi_0 + \mu_R B_R + \mu_E B_E + \mu_N B_N + \eta I\right) - \left(\frac{\lambda_R}{2} + \frac{1}{g_R+\omega_R}\right)B_R^2\right]dt \tag{7}$$

$$J_E=\max_{B_E\geq 0}\int_0^{\infty}e^{-\rho t}\left[\beta\left(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I\right)-\frac{\lambda_E}{2}B_E^2\right]dt \tag{8}$$

$$J_N=\max_{B_N\geq 0}\int_0^{\infty}e^{-\rho t}\left[(1-\alpha-\beta)\left(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I\right)-\frac{\lambda_N}{2}B_N^2\right]dt \tag{9}$$

Core enterprises, research institutions, and the government have continuous and differentiable profit functions $V_R(I)$, $V_E(I)$ and $V_N(I)$.

$$\rho V_R(I)=\max_{B_R\geq 0}\left[\alpha(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I)-\left(\frac{\lambda_R}{2}+\frac{1}{g_R+\omega_R}\right)B_R^2+V'_R(I)(\theta_R B_R+\theta_E B_E+\theta_N B_N-\varepsilon I)\right] \tag{10}$$

$$\rho V_E(I)=\max_{B_E\geq 0}\left[\beta(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I)-\frac{\lambda_E}{2}B_E^2+V'_E(I)(\theta_R B_R+\theta_E B_E+\theta_N B_N-\varepsilon I)\right] \tag{11}$$

$$\rho V_N(I)=\max_{B_N\geq 0}\left[(1-\alpha-\beta)(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I)-\frac{\lambda_N}{2}B_N^2+V'_N(I)(\theta_R B_R+\theta_E B_E+\theta_N B_N-\varepsilon I)\right] \tag{12}$$

Take the first-order partial derivatives of B_R, B_E, B_N for the right ends of (10) to (12) and make them equal to zero. The solution is:

$$B_R=\frac{\left(g_R+\omega_R\right)\left(\alpha\mu_R+\theta_R V'_R(I)\right)}{2+\lambda_R\left(g_R+\omega_R\right)}$$
$$B_E=\frac{\beta\mu_{\mathrm{E}}+\theta_{\mathrm{E}}V'_{\mathrm{E}}(I)}{\lambda_{\mathrm{E}}}$$
$$B_N=\frac{(1-\alpha-\beta)\mu_N+\theta_N V'_N(I)}{\lambda_N} \tag{13}$$

Bringing (13) into (10)~(12), simplification and collation gives:

$$\rho V_R(I)=[\alpha\eta-\varepsilon V'_R(I)]I+\frac{[\beta\mu_{\mathrm{E}}+\theta_{\mathrm{E}}V'_{\mathrm{E}}(I)][\alpha\mu_{\mathrm{E}}+\theta_{\mathrm{E}}V'_R(I)]}{\lambda_{\mathrm{E}}}+\frac{[(1-\alpha-\beta)\mu_N+\theta_N V'_N(I)][\alpha\mu_N+\theta_N V'_R(I)]}{\lambda_N}+\frac{(g_R+\omega_R)[\alpha\mu_R+\theta_R V'_R(I)]^2}{2[(g_R+\omega_R)\lambda_R+2]}+\alpha\pi_0 \tag{14}$$

$$\rho V_E(I)=[\beta\eta-\varepsilon V'_E(I)]I+\frac{(g_{\mathrm{R}}+\omega_R)[\beta\mu_{\mathrm{R}}+\theta_{\mathrm{R}}V'_{\mathrm{E}}(I)][\alpha\mu_{\mathrm{R}}+\theta_{\mathrm{R}}V'_R(I)]}{2+(g_{\mathrm{R}}+\omega_R)\lambda_{\mathrm{R}}}+\frac{[(1-\alpha-\beta)\mu_N+\theta_N V'_N(I)][\beta\mu_N+\theta_N V'_E(I)]}{\lambda_N}+\frac{[\beta\mu_E+\theta_E V'_E(I)]^2}{2\lambda_E}+\beta\pi_0 \tag{15}$$

$$\rho V_N(I)=[(1-\alpha-\beta)\eta-\varepsilon V'_N(I)]I+\frac{[\beta\mu_{\mathrm{E}}+\theta_{\mathrm{E}}V'_{\mathrm{E}}(I)][(1-\alpha-\beta)\mu_{\mathrm{E}}+\theta_{\mathrm{E}}V'_N(I)]}{\lambda_{\mathrm{E}}}+(1-\alpha-\beta)\pi_0+\frac{[(1-\alpha-\beta)\mu_N+\theta_N V'_N(I)]^2}{2\lambda_N}+\frac{(g_R+\omega_R)[(1-\alpha-\beta)\mu_R+\theta_R V'_N(I)][\alpha\mu_R+\theta_R V'_R(I)]}{(g_R+\omega_R)\lambda_R+2} \tag{16}$$

From the structure of (14) to (16), it can be seen that the solution to the HJB Equation is a unitary function I as the independent variable, and thus let:

$$V_R(I)=k_1 I+b_1$$
$$V_E(I)=k_2 I+b_2$$
$$V_N(I)=k_3 I+b_3 \tag{17}$$

Where k_1, k_2, k_3, b_1, b_2 and b_3 are constants, is solved:

$$V'_R(I)=\frac{dV_R(I)}{dI}=k_1$$
$$V'_E(I)=\frac{dV_E(I)}{dI}=k_2$$
$$V'_N(I)=\frac{dV_N(I)}{dI}=k_3 \tag{18}$$

Substituting (17) and (18) into (14)~(16) and collating gives:

$$\rho(k_1 I+b_1)=(\alpha\eta-\varepsilon k_1)I+\frac{(\beta\mu_{\mathrm{E}}+\theta_{\mathrm{E}}k_2)(\alpha\mu_{\mathrm{E}}+\theta_{\mathrm{E}}k_1)}{\lambda_{\mathrm{E}}}+\frac{[(1-\alpha-\beta)\mu_N+\theta_N k_3](\alpha\mu_N+\theta_N k_1)}{\lambda_N}$$

$$+\frac{(g_R+\omega_R)(\alpha\mu_R+\theta_R k_1)^2}{2[(g_R+\omega_R)\lambda_R+2]}+\alpha\pi_0 \tag{19}$$

$$\rho(k_2 I+b_2)=(\beta\eta-\varepsilon k_2)I$$
$$+\frac{(g_R+\omega_R)(\beta\mu_R+\theta_R k_2)(\alpha\mu_R+\theta_R k_1)}{2+(g_R+\omega_R)\lambda_R}$$
$$+\frac{[(1-\alpha-\beta)\mu_N+\theta_N k_3](\beta\mu_N+\theta_N k_2)}{\lambda_N}$$
$$+\frac{(\beta\mu_E+\theta_E k_2)^2}{2\lambda_E}+\beta\pi_0 \tag{20}$$

$$\rho(k_3 I+b_3)=[(1-\alpha-\beta)\eta-\varepsilon k_3]I$$
$$+\frac{(\beta\mu_E+\theta_E k_2)[(1-\alpha-\beta)\mu_E+\theta_E k_3]}{\lambda_E}+(1-\alpha-\beta)\pi_0$$
$$+\frac{[(1-\alpha-\beta)\mu_N+\theta_N k_3]^2}{2\lambda_N}$$
$$+\frac{(g_R+\omega_R)[(1-\alpha-\beta)\mu_R+\theta_R k_3](\alpha\mu_R+\theta_R k_1)}{(g_R+\omega_R)\lambda_R+2} \tag{21}$$

The values of the parameters of k_1, k_2, k_3, b_1, b_2 and b_3 can be obtained, respectively:

$$k_1=\frac{\alpha\eta}{\rho+\varepsilon} \tag{22}$$

$$k_2=\frac{\beta\eta}{\rho+\varepsilon} \tag{23}$$

$$k_3=\frac{(1-\alpha-\beta)\eta}{\rho+\varepsilon} \tag{24}$$

$$b_1=\frac{\alpha\pi_0}{\rho}+\frac{\alpha\beta\left[\eta\theta_E+\mu_E(\varepsilon+\rho)\right]^2}{\rho\lambda_E(\varepsilon+\rho)^2}$$
$$+\frac{\alpha(1-\alpha-\beta)\left[\eta\theta_N+\mu_N(\varepsilon+\rho)\right]^2}{\rho\lambda_N(\varepsilon+\rho)^2}$$
$$+\frac{\alpha^2(g_R+\omega_R)\left[\eta\theta_R+\mu_R(\varepsilon+\rho)\right]^2}{2\rho[(g_R+\omega_R)\lambda_R+2](\varepsilon+\rho)^2} \tag{25}$$

$$b_2=\frac{\beta\pi_0}{\rho}+\frac{\alpha\beta(g_R+\omega_R)\left[\eta\theta_R+\mu_R(\varepsilon+\rho)\right]^2}{\rho[(g_R+\omega_R)\lambda_R+2](\varepsilon+\rho)^2}$$
$$+\frac{\beta(1-\alpha-\beta)\left[\eta\theta_N+\mu_N(\varepsilon+\rho)\right]^2}{\rho\lambda_N(\varepsilon+\rho)^2}$$
$$+\frac{\beta^2\left[\eta\theta_E+\mu_E(\varepsilon+\rho)\right]^2}{2\rho\lambda_E(\varepsilon+\rho)^2} \tag{26}$$

$$b_3=\frac{(1-\alpha-\beta)\pi_0}{\rho}+\frac{\beta(1-\alpha-\beta)\left[\eta\theta_E+\mu_E(\varepsilon+\rho)\right]^2}{\rho\lambda_E(\varepsilon+\rho)^2}$$
$$+\frac{(1-\alpha-\beta)^2\left[\eta\theta_N+\mu_N(\varepsilon+\rho)\right]^2}{2\rho\lambda_N(\varepsilon+\rho)^2}$$
$$+\frac{\alpha(1-\alpha-\beta)(g_R+\omega_R)\left[\eta\theta_R+\mu_R(\varepsilon+\rho)\right]^2}{\rho[(g_R+\omega_R)\lambda_R+2](\varepsilon+\rho)^2} \tag{27}$$

Substituting k_1, k_2, k_3 into (13), the degree of collaborative data security governance efforts of core enterprises, research institutions, and the government is as follows:

$$B_{R_1}{}^*=\frac{\alpha(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]}{[(g_R+\omega_R)\lambda_R+2](\rho+\varepsilon)} \tag{28}$$

$$B_{E_1}{}^*=\frac{\beta[\mu_E(\rho+\varepsilon)+\theta_E\eta]}{\lambda_E(\rho+\varepsilon)} \tag{29}$$

$$B_{N_1}{}^*=\frac{(1-\alpha-\beta)[\mu_N(\rho+\varepsilon)+\theta_N\eta]}{\lambda_N(\rho+\varepsilon)} \tag{30}$$

Substituting each parameter in (22) to (27) into (17), the optimum payoff functions of the core enterprise, research institution, and government in this game scenario are found to be, respectively:

$$V_{R_1}(I)^*=\frac{\alpha\eta}{\rho+\varepsilon}I+\frac{\alpha\pi_0}{\rho}+\frac{\alpha\beta\left[\eta\theta_E+\mu_E(\varepsilon+\rho)\right]^2}{\rho\lambda_E(\varepsilon+\rho)^2}$$
$$+\frac{\alpha(1-\alpha-\beta)\left[\eta\theta_N+\mu_N(\varepsilon+\rho)\right]^2}{\rho\lambda_N(\varepsilon+\rho)^2}$$
$$+\frac{\alpha^2(g_R+\omega_R)\left[\eta\theta_R+\mu_R(\varepsilon+\rho)\right]^2}{2\rho[(g_R+\omega_R)\lambda_R+2](\varepsilon+\rho)^2} \tag{31}$$

$$V_{E_1}(I)^*=\frac{\beta\eta}{\rho+\varepsilon}I+\frac{\beta\pi_0}{\rho}+\frac{\alpha\beta(g_R+\omega_R)\left[\eta\theta_R+\mu_R(\varepsilon+\rho)\right]^2}{\rho[(g_R+\omega_R)\lambda_R+2](\varepsilon+\rho)^2}$$
$$+\frac{\beta(1-\alpha-\beta)\left[\eta\theta_N+\mu_N(\varepsilon+\rho)\right]^2}{\rho\lambda_N(\varepsilon+\rho)^2}+\frac{\beta^2\left[\eta\theta_E+\mu_E(\varepsilon+\rho)\right]^2}{2\rho\lambda_E(\varepsilon+\rho)^2} \tag{32}$$

$$V_{N_1}(I)^*=\frac{(1-\alpha-\beta)\eta}{\rho+\varepsilon}I+\frac{(1-\alpha-\beta)\pi_0}{\rho}$$
$$+\frac{\beta(1-\alpha-\beta)\left[\eta\theta_E+\mu_E(\varepsilon+\rho)\right]^2}{\rho\lambda_E(\varepsilon+\rho)^2}$$

$$+\frac{(1-\alpha-\beta)^2\left[\eta\theta_N+\mu_N(\varepsilon+\rho)\right]^2}{2\rho\lambda_N(\varepsilon+\rho)^2}+\frac{\alpha(1-\alpha-\beta)(g_R+\omega_R)\left[\eta\theta_R+\mu_R(\varepsilon+\rho)\right]^2}{\rho[(g_R+\omega_R)\lambda_R+2](\varepsilon+\rho)^2} \tag{33}$$

The overall profit equals the sum of the profits of the three participants, that is:

$$V_1(I)^*=\frac{\eta}{\rho+\varepsilon}I+\frac{\pi_0}{\rho}+\frac{\beta(2-\beta)\left[\eta\theta_E+\mu_E(\varepsilon+\rho)\right]^2}{2\rho\lambda_E(\varepsilon+\rho)^2}+\frac{\alpha(2-\alpha)(g_R+\omega_R)\left[\eta\theta_R+\mu_R(\varepsilon+\rho)\right]^2}{2\rho[(g_R+\omega_R)\lambda_R+2](\varepsilon+\rho)^2}+\frac{[1-(\alpha+\beta)^2]\left[\eta\theta_N+\mu_N(\varepsilon+\rho)\right]^2}{2\rho\lambda_N(\varepsilon+\rho)^2} \tag{34}$$

The Stackelberg Master-slave Game Model

In this game-theoretic scenario, the government is the leader in the collaborative governance of data security, while core enterprises and research organizations are the followers. To enhance the willingness of core companies and research organizations to engage in collaborative governance, the government has implemented certain incentive measures, assuming that the government incentive coefficients for the core companies and research organizations, respectively, are γ, δ. The core companies and scientific research organizations, as followers, will determine their own optimal decisions according to the government's decision-making to ensure that their interests are maximized. The government can anticipate the follow-up strategies of core companies and research organizations. The objective functions of the core firms, research institutes, and the government are:

$$J_R=\max_{B_R(t)\geq 0}\int_0^\infty e^{-\rho t}\left[\alpha\pi(t)-(1-\gamma(t))\left(\frac{\lambda_R}{2}+\frac{1}{g_R+\omega_R}\right)B_R^2(t)\right]dt \tag{35}$$

$$J_E=\max_{B_E(t)\geq 0}\int_0^\infty e^{-\rho t}\left[\beta\pi(t)-(1-\delta(t))\frac{\lambda_E}{2}B_E^2(t)\right]dt \tag{36}$$

$$J_N=\max_{B_N(t)\geq 0}\int_0^\infty e^{-\rho t}\left[(1-\alpha-\beta)\pi(t)-\frac{\lambda_N}{2}B_N^2(t)-\gamma(t)\left(\frac{\lambda_R}{2}+\frac{1}{g_R+\omega_R}\right)B_R^2(t)-\delta(t)\frac{\lambda_E}{2}B_E^2(t)\right]dt \tag{37}$$

Assuming that there exist continuous, bounded, and differentiable earnings functions $V_R(I)$, $V_E(I)$, $V_N(I)$ for core firms, research organizations, and the government. To solve the optimal decision-making problem of core companies and research organizations, we can obtain:

$$\rho V_R(I)=\max_{B_R\geq 0}\left[\alpha(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I)-(1-\gamma)\left(\frac{\lambda_R}{2}+\frac{1}{g_R+\omega_R}\right)B_R^2+V'_R(I)(\theta_R B_R+\theta_E B_E+\theta_N B_N-\varepsilon I)\right] \tag{38}$$

$$\rho V_E(I)=\max_{B_E\geq 0}\left[\beta(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I)-(1-\delta)\frac{\lambda_E}{2}B_E^2+V'_E(I)(\theta_R B_R+\theta_E B_E+\theta_N B_N-\varepsilon I)\right] \tag{39}$$

Solve for the right end of (38) and (39) by taking the first-order partial derivatives of B_R and B_E respectively and making them equal to zero:

$$B_R=\frac{(g_R+\omega_R)(\alpha\mu_R+\theta_R V'_R(I))}{(1-\gamma)[2+\lambda_R(g_R+\omega_R)]} \tag{40}$$

$$B_E=\frac{\beta\mu_{\mathrm{E}}+\theta_{\mathrm{E}}V'_{\mathrm{E}}(I)}{(1-\delta)\lambda_{\mathrm{E}}} \tag{41}$$

The government's HJB Equation can be expressed as:

$$\rho V_N(I)=\max_{B_N\geq 0}\left[(1-\alpha-\beta)(\pi_0+\mu_R B_R+\mu_E B_E+\mu_N B_N+\eta I)-\frac{\lambda_N}{2}B_N^2-\delta\frac{\lambda_E}{2}B_E^2+V'_N(I)(\theta_R B_R+\theta_E B_E+\theta_N B_N-\varepsilon I)-\gamma\left(\frac{\lambda_R}{2}+\frac{1}{g_R+\omega_R}\right)B_R^2\right] \tag{42}$$

Take the first-order partial derivative of Equation (42) B_N, and solve:

$$B_N=\frac{(1-\alpha-\beta)\mu_N+\theta_N V'_N(I)}{\lambda_N} \tag{43}$$

Substituting Equations (40) and (41) into (42), and taking the partial derivative of the first order of (42) concerning γ and δ, we obtain:

$$\gamma=\frac{(2-3\alpha-2\beta)\mu_R+\theta_R[2V'_N(I)-V'_R(I)]}{(2-\alpha-2\beta)\mu_R+\theta_R[2V'_N(I)+V'_R(I)]} \tag{44}$$

$$\delta=\frac{(2-2\alpha-3\beta)\mu_E+\theta_E[2V_N'(I)-V_E'(I)]}{(2-2\alpha-\beta)\mu_E+\theta_E[2V_N'(I)+V_E'(I)]} \tag{45}$$

Substituting (40), (41), (43)~(45) into (38), (39), (42), we simplify to obtain:

$$\rho V_R(I)=\left(\alpha\eta-\varepsilon V_R'(I)\right)I+\alpha\pi_0$$
$$+\frac{(g_R+\omega_R)(\alpha\mu_R+\theta_R V_R'(I))[(2-\alpha-2\beta)\mu_R+\theta_R\left(2V_N'(I)+V_R'(I)\right)]}{4[2+\lambda_R(g_R+\omega_R)]}$$
$$+\frac{\left(\alpha\mu_E+\theta_E V_R'(I)\right)[(2-2\alpha-\beta)\mu_E+\theta_E\left(V_E'(I)+2V_N'(I)\right)]}{2\lambda_E}$$
$$+\frac{\left(\alpha\mu_N+\theta_N V_R'(I)\right)\left[(1-\alpha-\beta)\mu_N+\theta_N V_N'(I)\right]}{\lambda_N} \tag{46}$$

$$\rho V_E(I)=\left(\beta\eta-\varepsilon V_E'(I)\right)I+\beta\pi_0$$
$$+\frac{(\beta\mu_E+\theta_E V_E'(I))[(2-2\alpha-\beta)\mu_E+\theta_E\left(V_E'(I)+2V_N'(I)\right)]}{4\lambda_E}$$
$$+\frac{(g_R+\omega_R)\left(\beta\mu_R+\theta_R V_E'(I)\right)[(2-\alpha-2\beta)\mu_R+\theta_R\left(V_R'(I)+2V_N'(I)\right)]}{2[2+\lambda_R(g_R+\omega_R)]}$$
$$+\frac{\left(\beta\mu_N+\theta_N V_E'(I)\right)\left[(1-\alpha-\beta)\mu_N+\theta_N V_N'(I)\right]}{\lambda_N} \tag{47}$$

$$\rho V_N(I)=[(1-\alpha-\beta)\eta-\varepsilon V_N'(I)]I+(1-\alpha-\beta)\pi_0$$
$$+\frac{[(2-2\alpha-\beta)\mu_E+\theta_E\left(V_E'(I)+2V_N'(I)\right)]^2}{8\lambda_E}$$
$$+\frac{(g_R+\omega_R)[(2-\alpha-2\beta)\mu_R+\theta_R\left(V_R'(I)+2V_N'(I)\right)]^2}{8[2+\lambda_R(g_R+\omega_R)]}$$
$$+\frac{\left[(1-\alpha-\beta)\mu_N+\theta_N V_N'(I)\right]^2}{2\lambda_N} \tag{48}$$

From the structure of (46) to (48), the solution to the HJB Equation is a linear function of I as the independent variable.

$$\begin{aligned} V_R(I)&=k_1I+b_1\\ V_E(I)&=k_2I+b_2\\ V_N(I)&=k_3I+b_3 \end{aligned} \tag{49}$$

Where k_1, k_2, k_3, b_1, b_2, b_3 are constants, and the first-order partial derivatives of $V_R(I)$, $V_E(I)$ and $V_N(I)$ are obtained. Bring (49) and its partial derivative of first order into (46)~(48), and then we can get the result:

$$\rho(k_1I+b_1)=\left(\alpha\eta-\varepsilon k_1\right)I+\alpha\pi_0$$
$$+\frac{(g_R+\omega_R)(\alpha\mu_R+\theta_R k_1)[(2-\alpha-2\beta)\mu_R+\theta_R\left(2k_3+k_1\right)]}{4[2+\lambda_R(g_R+\omega_R)]}$$
$$+\frac{\left(\alpha\mu_E+\theta_E k_1\right)[(2-2\alpha-\beta)\mu_E+\theta_E\left(k_2+2k_3\right)]}{2\lambda_E}$$
$$+\frac{\left(\alpha\mu_N+\theta_N k_1\right)\left[(1-\alpha-\beta)\mu_N+\theta_N k_3\right]}{\lambda_N} \tag{50}$$

$$\rho(k_2I+b_2)=\left(\beta\eta-\varepsilon k_2\right)I+\beta\pi_0$$
$$+\frac{(\beta\mu_E+\theta_E k_2)[(2-2\alpha-\beta)\mu_E+\theta_E\left(k_2+2k_3\right)]}{4\lambda_E}$$
$$+\frac{(g_R+\omega_R)\left(\beta\mu_R+\theta_R k_2\right)[(2-\alpha-2\beta)\mu_R+\theta_R\left(k_1+2k_3\right)]}{2[2+\lambda_R(g_R+\omega_R)]}$$
$$+\frac{\left(\beta\mu_N+\theta_N k_2\right)\left[(1-\alpha-\beta)\mu_N+\theta_N k_3\right]}{\lambda_N} \tag{51}$$

$$\rho(k_3I+b_3)=[(1-\alpha-\beta)\eta-\varepsilon k_3]I+(1-\alpha-\beta)\pi_0$$
$$+\frac{[(2-2\alpha-\beta)\mu_E+\theta_E\left(k_2+2k_3\right)]^2}{8\lambda_E}$$
$$+\frac{(g_R+\omega_R)[(2-\alpha-2\beta)\mu_R+\theta_R\left(k_1+2k_3\right)]^2}{8[2+\lambda_R(g_R+\omega_R)]}$$
$$+\frac{\left[(1-\alpha-\beta)\mu_N+\theta_N k_3\right]^2}{2\lambda_N} \tag{52}$$

The parameter values of k_1, k_2, k_3, b_1, b_2, b_3 are obtained, respectively:

$$k_1=\frac{\alpha\eta}{\rho+\varepsilon} \tag{53}$$

$$k_2=\frac{\beta\eta}{\rho+\varepsilon} \tag{54}$$

$$k_3=\frac{(1-\alpha-\beta)\eta}{\rho+\varepsilon} \tag{55}$$

$$b_1=\frac{\alpha\pi_0}{\rho}+\frac{\alpha(g_R+\omega_R)(2-\alpha-2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{4\rho[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)^2}$$
$$+\frac{\alpha(2-2\alpha-\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2}$$
$$+\frac{\alpha(1-\alpha-\beta)[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{\rho\lambda_N(\rho+\varepsilon)^2} \tag{56}$$

$$b_2=\frac{\beta\pi_0}{\rho}+\frac{\beta(g_R+\omega_R)(2-\alpha-2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)^2}$$
$$+\frac{\beta(2-2\alpha-\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{4\rho\lambda_E(\rho+\varepsilon)^2}$$

$$+\frac{\beta(1-\alpha-\beta)[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{\rho\lambda_N(\rho+\varepsilon)^2} \tag{57}$$

$$b_3=\frac{(1-\alpha-\beta)\ \pi_0}{\rho}$$
$$+\frac{(g_R+\omega_R)(2-\alpha-2\beta)^2[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{8\rho[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)^2}$$
$$+\frac{(2-2\alpha-\beta)^2[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{8\rho\lambda_E(\rho+\varepsilon)^2}$$
$$+\frac{(1-\alpha-\beta)^2[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{58}$$

Bringing (53) to (55) into (44) and (45), the optimum excitation factor of the government for core firms and research institutes is found to be, respectively:

$$\gamma=\frac{2-3\alpha-2\beta}{2-\alpha-2\beta} \tag{59}$$

$$\delta=\frac{2-2\alpha-3\beta}{2-2\alpha-\beta} \tag{60}$$

Bringing (53)~(55), (59), and (60) into (40), (41), and (43), we can obtain the level of collaborative data security governance efforts of core enterprises, research institutes, and governments, respectively:

$$B_{R_2}{}^*=\frac{(g_R+\omega_R)(2-\alpha-2\beta)\left[\mu_R(\rho+\varepsilon)+\theta_R\eta\right]}{2[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)} \tag{61}$$

$$B_{E_2}{}^*=\frac{(2-2\alpha-\beta)\left[\mu_E(\rho+\varepsilon)+\theta_E\eta\right]}{2\lambda_E(\rho+\varepsilon)} \tag{62}$$

$$B_{N_2}{}^*=\frac{(1-\alpha-\beta)\left[\mu_N(\rho+\varepsilon)+\theta_N\eta\right]}{\lambda_N(\rho+\varepsilon)} \tag{63}$$

Substituting k_1, k_2, k_3, b_1, b_2, b_3 into (49), the optimal revenue functions for the core firm, the research institution, and the government are obtained, respectively:

$$V_{R_2}(I)^*=\frac{\alpha\eta}{\rho+\varepsilon}I+\frac{\alpha\pi_0}{\rho}$$
$$+\frac{\alpha(g_R+\omega_R)(2-\alpha-2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{4\rho[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)^2}$$
$$+\frac{\alpha(2-2\alpha-\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2}$$
$$+\frac{\alpha(1-\alpha-\beta)[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{\rho\lambda_N(\rho+\varepsilon)^2} \tag{64}$$

$$V_{E_2}(I)^*=\frac{\beta\eta}{\rho+\varepsilon}I+\frac{\beta\pi_0}{\rho}$$
$$+\frac{\beta(g_R+\omega_R)(2-\alpha-2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)^2}$$
$$+\frac{\beta(2-2\alpha-\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{4\rho\lambda_E(\rho+\varepsilon)^2}$$
$$+\frac{\beta(1-\alpha-\beta)[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{\rho\lambda_N(\rho+\varepsilon)^2} \tag{65}$$

$$V_{N_2}(I)^*=\frac{(1-\alpha-\beta)\eta}{\rho+\varepsilon}I+\frac{(1-\alpha-\beta)\ \pi_0}{\rho}$$
$$+\frac{(g_R+\omega_R)(2-\alpha-2\beta)^2[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{8\rho[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)^2}$$
$$+\frac{(2-2\alpha-\beta)^2[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{8\rho\lambda_E(\rho+\varepsilon)^2}$$
$$+\frac{(1-\alpha-\beta)^2[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{66}$$

Thus, the optimal return to the innovation ecosystem in this model can be found to be:

$$V_2(I)^*=\frac{\eta I}{\rho+\varepsilon}+\frac{\pi_0}{\rho}$$
$$+\frac{(g_R+\omega_R)[4-(\alpha+2\beta)^2][\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{8\rho[2+\lambda_R(g_R+\omega_R)](\rho+\varepsilon)^2}$$
$$+\frac{[4-(2\alpha+\beta)^2][\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{8\rho\lambda_E(\rho+\varepsilon)^2}$$
$$+\frac{[1-(\alpha+\beta)^2][\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{67}$$

Collaborative Game Model

In this game-theoretic scenario, core enterprises, research institutions, and the government collaboratively participate in data security governance. The three parties work together to jointly improve governance levels, with each entity aiming to maximize the revenue of the innovation ecosystem and minimize the environmental impact, and collectively determine the optimum degree of effort and the optimum function. The common objective function of core firms, research institutions, and the government is:

$$\max_{B_{R(t)}B_{E(t)}B_{N(t)}} J=\int_0^\infty e^{-\rho t}\left[\pi(t)-\left(\frac{\lambda_R}{2}+\frac{1}{g_R+\omega_R}\right)B_R^2-\frac{\lambda_E}{2}B_E^2-\frac{\lambda_N}{2}B_N^2\right]dt \tag{68}$$

Assuming that the innovation ecosystem has an optimal function $V(I)$, which is continuous, bounded, and differentiable.

$$\rho V(I)=\max_{B_{R(t)},B_{E(t)},B_{N(t)}\geq 0}\{\pi(t)-\left(\frac{\lambda_R}{2}+\frac{1}{g_R+\omega_R}\right)B_R^2-\frac{\lambda_E}{2}B_E^2-\frac{\lambda_N}{2}B_N^2+V'(I)(\theta_R B_R+\theta_E B_E+\theta_N B_N-\varepsilon I)\} \tag{69}$$

Take the partial derivative of the first order of Equation (69) concerning B_R, B_E, B_N and make them equal to zero:

$$B_R=\frac{(g_R+\omega_R)\left(\mu_R+\theta_R V'(I)\right)}{2+(g_R+\omega_R)\lambda_R}$$
$$B_E=\frac{\mu_E+\theta_E V'(I)}{\lambda_E}$$
$$B_N=\frac{\mu_N+\theta_N V'(I)}{\lambda_N} \tag{70}$$

The solution is obtained by bringing (70) into (69) and simplifying:

$$\rho V(I)=[\eta-\varepsilon V'(I)]I+\pi_0+\frac{[\mu_E+\theta_E V'(I)]^2}{2\lambda_E}+\frac{(g_R+\omega_R)[\mu_R+\theta_R V'(I)]^2}{2[2+(g_R+\omega_R)\lambda_R]}+\frac{[\mu_N+\theta_N V'(I)]^2}{2\lambda_N} \tag{71}$$

Observing the form of (71) shows that the solution to the HJB Equation is a unitary function I as the independent variable, such that:

$$V(I)=k_1 I+b_1 \tag{72}$$

Where k_1 and b_1 are constants, for which the solution is shown in (73):

$$V'(I)=\frac{dV(I)}{dI}=k_1 \tag{73}$$

Bringing (72) and (73) into (71) yields:

$$\rho(k_1 I+b_1)=(\eta-\varepsilon k_1)I+\pi_0+\frac{(\mu_E+\theta_E k_1)^2}{2\lambda_E}+\frac{(g_R+\omega_R)(\mu_R+\theta_R k_1)^2}{2[2+(g_R+\omega_R)\lambda_R]}+\frac{(\mu_N+\theta_N k_1)^2}{2\lambda_N} \tag{74}$$

From the above assumptions, $V(I)$ is satisfied for all $I\geq 0$ and hence k_1 and b_1 can be obtained respectively:

$$k_1=\frac{\eta}{\rho+\varepsilon} \tag{75}$$

$$b_1=\frac{\pi_0}{\rho}+\frac{[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2}+\frac{(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2}+\frac{[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{76}$$

Bringing (75) into (70) yields the optimal level of effort for collaborative governance for each subject, respectively:

$$B_{R_3}^*=\frac{(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]}{[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)} \tag{77}$$

$$B_{E_3}^*=\frac{\mu_E(\rho+\varepsilon)+\theta_E\eta}{\lambda_E(\rho+\varepsilon)} \tag{78}$$

$$B_{N_3}^*=\frac{\mu_N(\rho+\varepsilon)+\theta_N\eta}{\lambda_N(\rho+\varepsilon)} \tag{79}$$

Bringing k_1 and b_1 into (72), the optimal revenue function of the system is:

$$V_3(I)^*=\frac{\eta}{\rho+\varepsilon}I+\frac{\pi_0}{\rho}+\frac{[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2}+\frac{(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2}+\frac{[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{80}$$

According to the partition coefficient of the revenues of each of the core companies, research organizations, and the government, the optimal benefit functions of the three main parties are found, respectively:

$$V_{R_3}(I)^* = \frac{\alpha\eta}{\rho+\varepsilon}I + \frac{\alpha\pi_0}{\rho} + \frac{\alpha[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2} + \frac{\alpha(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{\alpha[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{81}$$

$$V_{E_3}(I)^* = \frac{\beta\eta}{\rho+\varepsilon}I + \frac{\beta\pi_0}{\rho} + \frac{\beta[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2} + \frac{\beta(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{\beta[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{82}$$

$$V_{N_3}(I)^* = \frac{(1-\alpha-\beta)\eta}{\rho+\varepsilon}I + \frac{(1-\alpha-\beta)\pi_0}{\rho} + \frac{(1-\alpha-\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2} + \frac{(1-\alpha-\beta)(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{(1-\alpha-\beta)[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} \tag{83}$$

Results and Discussion

Comparative Analysis of Model Results

Comparative analysis of three models has led to the following relevant conclusions:

Proposition 1: In Nash non-cooperative games and Stackelberg leader-follower games, the government's level of effort to participate in collaborative data security governance remains unchanged. However, in the governance process, the government offers certain incentives to the core companies and research organizations will significantly increase the level of collaborative willingness of the core companies and research organizations, and the magnitude of improvement is equal to the optimum excitation coefficient of the government to the core companies and research organizations. That is:

(1) Comparison of the optimal effort levels of core enterprises

$$B_{R_1}{}^* < B_{R_2}{}^* < B_{R_3}{}^* \tag{84}$$

(2) Comparison of the optimal effort levels of scientific research institutions

$$B_{E_1}{}^* < B_{E_2}{}^* < B_{E_3}{}^* \tag{85}$$

(3) Comparison of the optimal effort levels of government

$$B_{N_1}{}^* = B_{N_2}{}^* < B_{N_3}{}^* \tag{86}$$

(4) Optimal incentive coefficients

$$\gamma^* = \frac{B_{R_2}{}^* - B_{R_1}{}^*}{B_{R_2}{}^*}\left(0<\gamma<\frac{2}{3}\right)$$
$$\delta^* = \frac{B_{E_2}{}^* - B_{E_1}{}^*}{B_{E_2}{}^*}\left(0<\delta<\frac{2}{3}\right) \tag{87}$$

Proof:

$$B_{R_2}{}^* - B_{R_1}{}^* = \frac{(g_R+\omega_R)(2-3\alpha-2\beta)\left[\mu_R(\rho+\varepsilon)+\theta_R\eta\right]}{2[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)} = \frac{(2-3\alpha-2\beta)}{(2-\alpha-2\beta)} \bullet \frac{(g_R+\omega_R)(2-\alpha-2\beta)\left[\mu_R(\rho+\varepsilon)+\theta_R\eta\right]}{2[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)} = \gamma^* \bullet B_{R_2}{}^* > 0 \tag{88}$$

$$B_{R_3}{}^* - B_{R_2}{}^* = \frac{(g_R+\omega_R)(\alpha+2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]}{2[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)} > 0 \tag{89}$$

$$B_{E_2}{}^* - B_{E_1}{}^* = \frac{(2-2\alpha-3\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]}{2\lambda_E(\rho+\varepsilon)} = \frac{2-2\alpha-3\beta}{2-2\alpha-\beta} \bullet \frac{(2-2\alpha-\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]}{2\lambda_E(\rho+\varepsilon)} = \delta \bullet B_{E_2}{}^* > 0 \tag{90}$$

$$B_{E_3}{}^* - B_{E_2}{}^* = \frac{(2\alpha+\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]}{2\lambda_E(\rho+\varepsilon)} > 0 \tag{91}$$

$$B_{N_2}{}^* = B_{N_1}{}^* \tag{92}$$

$$B_{N_3}{}^* - B_{N_2}{}^* = \frac{(\alpha+\beta)[\mu_N(\rho+\varepsilon)+\theta_N\eta]}{\lambda_N(\rho+\varepsilon)} > 0 \tag{93}$$

Proposition 2: In the Stackelberg leader-follower game model, the optimum payoffs for the participants are all greater than those in the Nash non-cooperative game model, as shown in (94).

$$V_{R_2}(I)^* > V_{R_1}(I)^*$$
$$V_{E_2}(I)^* > V_{E_1}(I)^*$$
$$V_{N_2}(I)^* > V_{N_1}(I)^* \tag{94}$$

Proof:

$$V_{R_2}(I)^* - V_{R_1}(I)^* = \frac{\alpha(g_R+\omega_R)(2-3\alpha-2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{4\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{\alpha(2-2\alpha-3\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{2\rho\lambda_E(\rho+\varepsilon)^2} > 0 \tag{95}$$

$$V_{E_2}(I)^* - V_{E_1}(I)^* = \frac{\beta(g_R+\omega_R)(2-3\alpha-2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{2\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{\beta(2-2\alpha-3\beta)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{4\rho\lambda_E(\rho+\varepsilon)^2} > 0 \tag{96}$$

$$V_{N_2}(I)^* - V_{N_1}(I)^* = \frac{(g_R+\omega_R)(2-3\alpha-2\beta)^2[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{8\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{(2-2\alpha-3\beta)^2[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{8\rho\lambda_E(\rho+\varepsilon)^2} > 0 \tag{97}$$

Proposition 3: The order of optimum returns to the innovation ecosystem in the three models is: the collaborative model has the highest return, the Stackelberg leader-follower game has the second highest return, and the Nash non-cooperative game has the lowest return, as shown in (98).

$$V_3(I)^* > V_2(I)^* > V_1(I)^* \tag{98}$$

Proof:

$$V_2(I)^* - V_1(I)^*$$
$$= \frac{(g_R+\omega_R)(3\alpha+2\beta-2)(\alpha-2-2\beta)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{8\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{(2\alpha+3\beta-2)(-2\alpha+\beta-2)[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{8\rho\lambda_E(\rho+\varepsilon)^2} > 0 \tag{99}$$

$$V_3(I)^* - V_2(I)^* = \frac{(2\alpha+\beta)^2[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{8\rho\lambda_E(\rho+\varepsilon)^2} + \frac{(g_R+\omega_R)(\alpha+2\beta)^2[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{8\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2} + \frac{(\alpha+\beta)^2[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{2\rho\lambda_N(\rho+\varepsilon)^2} > 0 \tag{100}$$

Proposition 4: The optimal incentive coefficient is negatively correlated with the profit distribution coefficient, i.e. the more revenue-sharing core enterprises and research institutions receive, the less government policy support and various subsidies they receive.

Proof: It can be obtained from (59), (60), where $0<\gamma<\frac{2}{3}$, $0<\beta<\frac{2}{3}$

$$\frac{\partial\gamma^*}{\partial\alpha} = \frac{4(\beta-1)}{(2-\alpha-2\beta)^2} < 0, \quad \frac{\partial\gamma^*}{\partial\beta} = -\frac{4\alpha}{(2-\alpha-2\beta)^2} < 0$$
$$\frac{\partial\delta^*}{\partial\alpha} = -\frac{4\beta}{(2-2\alpha-\beta)^2} < 0, \quad \frac{\partial\delta^*}{\partial\beta} = \frac{4(\alpha-1)}{(2-2\alpha-\beta)^2} < 0 \tag{101}$$

Proposition 5: When the benefit distribution coefficients α, β meet the conditions of Equation (104), it can achieve Pareto optimality for the three types of subjects.

Proof:

$$z_1 = \frac{(g_R+\omega_R)[\mu_R(\rho+\varepsilon)+\theta_R\eta]^2}{\rho[2+(g_R+\omega_R)\lambda_R](\rho+\varepsilon)^2}$$
$$z_2 = \frac{[\mu_E(\rho+\varepsilon)+\theta_E\eta]^2}{\rho\lambda_E(\rho+\varepsilon)^2}$$
$$z_3 = \frac{[\mu_N(\rho+\varepsilon)+\theta_N\eta]^2}{\rho\lambda_N(\rho+\varepsilon)^2} \tag{102}$$

$$\frac{\alpha}{2}z_1 + \frac{\alpha}{2}z_2 + \frac{\alpha}{2}z_3 \ge \frac{(2-\alpha-2\beta)\alpha}{4}z_1 + \frac{\alpha(2-2\alpha-\beta)}{2}z_2 + \alpha(1-\alpha-\beta)z_3$$
$$\frac{\beta}{2}z_1 + \frac{\beta}{2}z_2 + \frac{\beta}{2}z_3 \ge \frac{\beta(2-\alpha-2\beta)}{2}z_1 + \frac{\beta(2-2\alpha-\beta)}{4}z_2 + \beta(1-\alpha-\beta)z_3$$
$$\frac{1-\alpha-\beta}{2}z_1 + \frac{1-\alpha-\beta}{2}z_2 + \frac{1-\alpha-\beta}{2}z_3 \ge \frac{(2-\alpha-2\beta)^2}{8}z_1 + \frac{(2-2\alpha-\beta)^2}{8}z_2 + \frac{(1-\alpha-\beta)^2}{2}z_3 \tag{103}$$

Simplifying (103) gives the following result:

$$z_1+z_2+z_3 \ge \frac{(2-\alpha-2\beta)}{2}z_1 + (2-2\alpha-\beta)z_2 + 2(1-\alpha-\beta)z_3$$
$$z_1+z_2+z_3 \ge (2-\alpha-2\beta)z_1 + \frac{(2-2\alpha-\beta)}{2}z_2 + 2(1-\alpha-\beta)z_3$$
$$z_1+z_2+z_3 \ge \frac{(2-\alpha-2\beta)^2}{4(1-\alpha-\beta)}z_1 + \frac{(2-2\alpha-\beta)^2}{4(1-\alpha-\beta)}z_2 + (1-\alpha-\beta)z_3 \tag{104}$$

According to (103) and (104), it can be seen that $V_{R_3}(I)^* > V_{R_2}(I)^*$, $V_{E_3}(I)^* > V_{E_2}(I)^*$, $V_{N_3}(I)^* > V_{N_2}(I)^*$ it follows from (94) that $V_{R_2}(I)^* > V_{R_1}(I)^*$, $V_{E_2}(I)^* > V_{E_1}(I)^*$,

$V_{N_2}(I)^* > V_{N_1}(I)^*$, thus prove that $V_{R_3}(I)^* > V_{R_2}(I)^* > V_{R_2}(I)^*$, $V_{E_3}(I)^* > V_{E_2}(I)^* > V_{E_1}(I)^*$, $V_{N_3}(I)^* > V_{N_2}(I)^* > V_{N_1}(I)^*$.

Proposition 6: Under the Stackelberg leader-follower game, the effort degree of core firms and scientific research institutions is positively correlated with the incentive coefficient of the government.

Proof:

$$\frac{\partial B_{R_2}{}^*}{\partial \gamma} = \frac{\alpha\left(\eta\theta_R + \mu_R(\varepsilon+\rho)\right)\left(g_R+\omega_R\right)}{\left(1-\gamma\right)^2(\varepsilon+\rho)\left[2+\lambda_R\left(g_R+\omega_R\right)\right]} > 0$$

$$\frac{\partial B_{E_2}{}^*}{\partial \delta} = \frac{\beta\left(\eta\theta_E + \mu_E(\varepsilon+\rho)\right)}{\left(1-\delta\right)^2(\varepsilon+\rho)\lambda_E} > 0 \tag{105}$$

Corollary 1: Under different game mechanisms, the optimal strategy of data safety collaborative governance of the three parties will increase with the increase of the coefficient of data safety collaborative governance ability, the coefficient of the impact of effort on the total benefit, the coefficient of the core enterprise's technological innovation ability, the coefficient of the core enterprise's ability to assess the risk of data security, and decrease with the increase of the coefficient of the cost of data safety collaborative governance, and the rate of decay of the willingness to collaborate.

Simulation Analysis of Algorithms and Discussion

The superscript N stands for Nash non-cooperative game, the superscript S stands for Stackelberg leader-follower game, and the superscript C stands for cooperative game. In this paper, we refer to the way the parameters are set in the related literature [39] and assign values to the parameters in the context of the actual situation of data safety governance and the government's incentive policies, and the algorithm is simulated and analyzed using Matlab software. In this paper, the relevant parameters are set as shown in Table 2.

The optimal strategies and optimal revenue of the core enterprises, research institutes, government, and the overall optimal revenue of the system are found as shown in Tables 3 and 4.

Substituting the results of the above assignments into the three decision scenarios, the expressions for the optimal returns of the core business, the research organization, the government, and the system are obtained, as shown in Tables 5 and 6.

Figs 2-5 represent the change curves of synergistic benefits of core firms, research organizations, government, and the three parties as a whole in different game scenarios.

Table 4. Assignment results (→).

Government		Innovation ecosystem
Optimal strategy	Optimal revenue	Overall optimal revenue
$B_N{}^N = 0.85$	$V_N{}^N = 7.0496$	$V^N = 24.8383$
$B_N{}^S = 0.85$	$V_N{}^S = 7.6604$	$V^S = 29.1843$
$B_N{}^C = 2.8333$	$V_N{}^C = 12.3008$	$V^C = 41.0028$

Table 2. Parameter setting.

Parameter	Numeric	Parameter	Numeric	Parameter	Numeric	Parameter	Numeric	Parameter	Numeric
$I(0)$	1	λ_R	0.5	λ_E	0.4	λ_N	0.3	g_R	0.3
ω_R	0.2	θ_R	0.5	θ_E	0.4	θ_N	0.3	ε	0.1
μ_R	0.7	μ_E	0.5	μ_N	0.4	η	0.3	α	0.5
β	0.2	ρ	0.1						

Table 3. Assignment results (→).

Core enterprise		Scientific research institution	
Optimal strategy	Optimal revenue	Optimal strategy	Optimal revenue
$B_R{}^N = 0.1611$	$V_R{}^N = 12.9715$	$B_E{}^N = 0.55$	$V_E{}^N = 4.8172$
$B_R{}^S = 0.1772$	$V_R{}^S = 16.0549$	$B_E{}^S = 1.1$	$V_E{}^S = 5.4689$
$B_R{}^C = 0.3222$	$V_R{}^C = 20.5014$	$B_E{}^C = 2.75$	$V_E{}^C = 8.2006$

Table 5. Optimal revenue expression (→).

Core enterprise	Scientific research institution
$V_R{}^N = 16.38813 - 3.41663e^{-0.1t}$	$V_E{}^N = 6.18385 - 1.36665e^{-0.1t}$
$V_R{}^S = 21.1819 - 5.127e^{-0.1t}$	$V_E{}^S = 7.5197 - 2.0508e^{-0.1t}$
$V_R{}^C = 35.58458 - 15.08318e^{-0.1t}$	$V_E{}^C = 14.23387 - 6.03327e^{-0.1t}$

Table 6. Optimal revenue expression (→).

Government	Overall system revenue
$V_N{}^N = 9.09958 - 2.04998e^{-0.1t}$	$V^N = 31.67155 - 6.83325e^{-0.1t}$
$V_N{}^S = 10.7366 - 3.0762e^{-0.1t}$	$V^S = 39.4383 - 10.254e^{-0.1t}$
$V_N{}^C = 21.35071 - 9.04991e^{-0.1t}$	$V^C = 71.16915 - 30.16635e^{-0.1t}$

As can be seen from Figs 2-5, the optimal collaborative gains of core enterprises, research institutions, and government, as well as the optimal collaborative gains of the system as a whole, gradually become larger with the increase of time. The magnitude of increase is larger in the initial stage, smaller in the subsequent stage, and finally tends to stabilize. In the three decision-making situations, both for the participating subjects and the innovation ecosystem as a whole, the optimal return under the cooperative game mode is the highest, followed by the Stackelberg leader-follower game. The non-cooperative game yields the lowest return. When the government adopts incentives for core enterprises and scientific research institutes, the returns for core enterprises, scientific research institutes, and the system as a whole increase. Therefore, Propositions 1-3 are proved.

The above results indicate that the collaborative cooperation mechanism under government incentives can comprehensively and effectively enhance the revenue levels of data security governance for core enterprises, research institutions, the government, and the system as a whole. Therefore, the government can provide tax reductions or tax credits to core enterprises and research institutions that actively participate in data security governance. Special financial subsidy funds should be established to support core enterprises and research institutions in carrying out data security

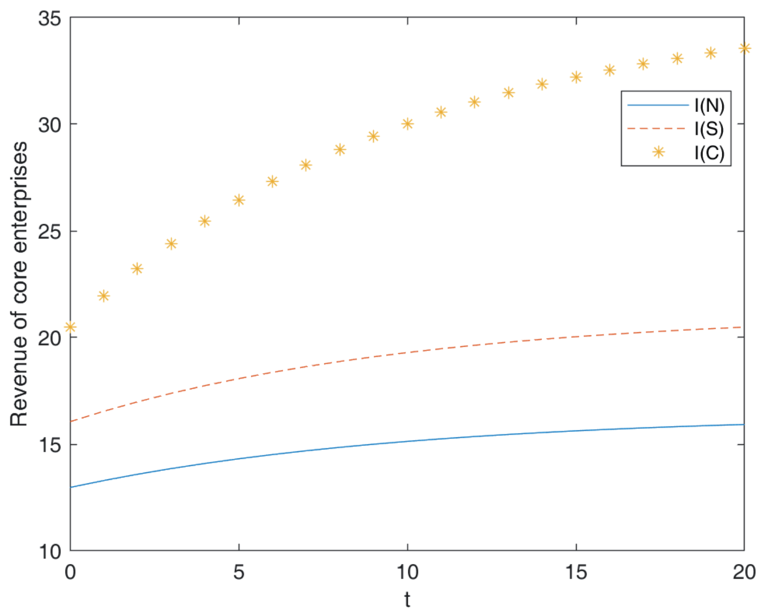


Fig. 2. Optimal benefits for core enterprises.

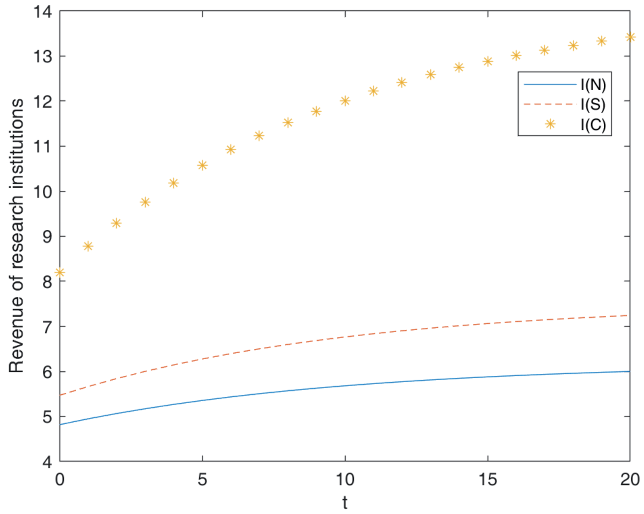


Fig. 3. Optimal benefits for scientific research institutions.

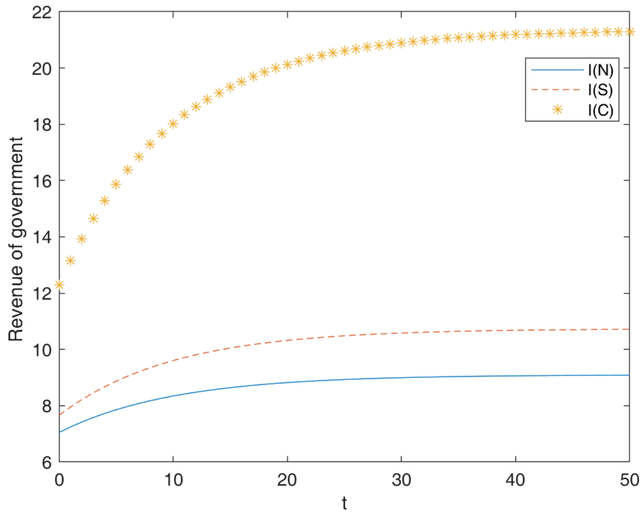


Fig. 4. Optimal benefits for the government.

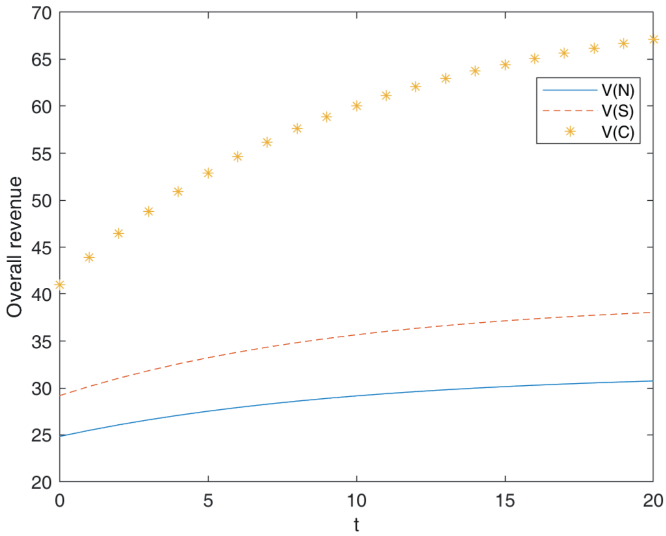


Fig. 5. Optimal benefits for the system.

projects. Additionally, rewards should be given to core enterprises and research institutions that introduce high-end data security talent.

However, it is worth noting that as the government gradually increases the subsidy for the participation of core companies and research organizations, the willingness of core companies and research organizations to collaborate and the perceived benefits show a stable trend over time, which may be attributed to the change in the adaptation and expectation of the subsidy by both, as well as the potential saturation point that exists in the process of collaborative governance of data security. Therefore, this finding is important for understanding the dynamic participation behaviors of core firms and research institutions under the master-slave game model, as well as the effective adjustment of subsidy policies.

Figs 6-10 represent the evolutionary trend of the optimum returns of the innovation ecosystem under the synergistic influence of key parameters and time in the collaborative cooperation game model.

From Figs 6 and 7, it can be seen that the governance capacity coefficient and the effort level coefficient have a positive influence on the innovation ecosystem. The magnitude of this impact gradually increases over time, and the effects of governance capacity and effort level on total returns are generally consistent. In contrast, the government's governance capacity has the largest impact on total returns, and core firms have the smallest impact on total returns. Therefore, to enhance the level of collaborative data security governance in the metaverse, the government should lead core enterprises and research institutions in taking proactive measures. The government should encourage research institutions and enterprises to increase investment in the research

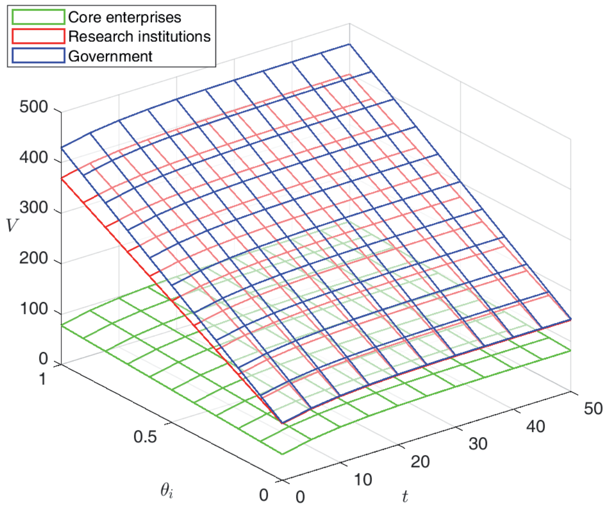


Fig. 6. Effect of θ_R , θ_E , θ_N and t on $V_3(I)^*$.

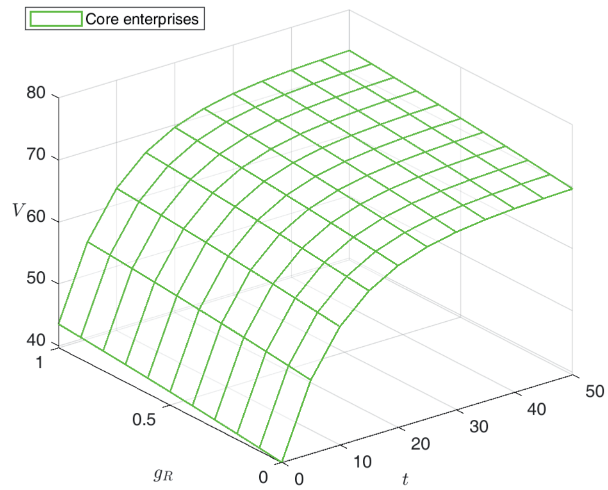


Fig. 8. Effect of g_R and t on $V_3(I)^*$.

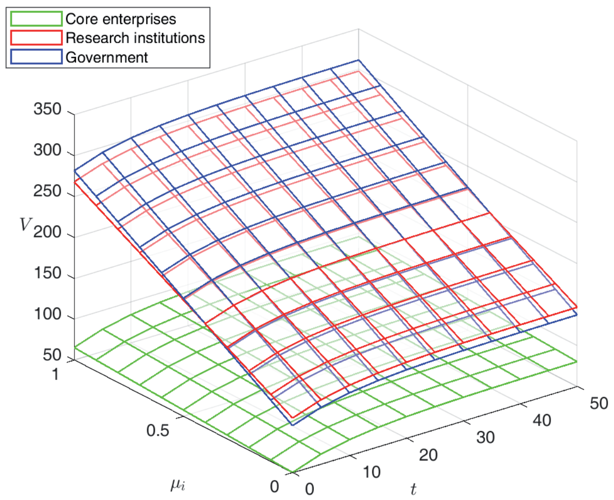


Fig. 7. Effect of μ_R , μ_E , μ_N and t on $V_3(I)^*$.

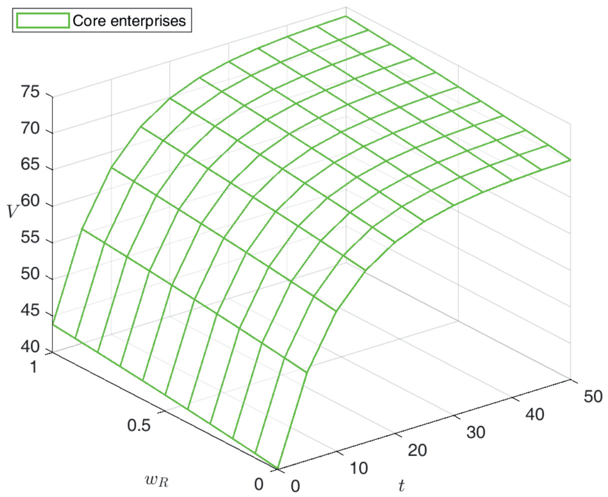
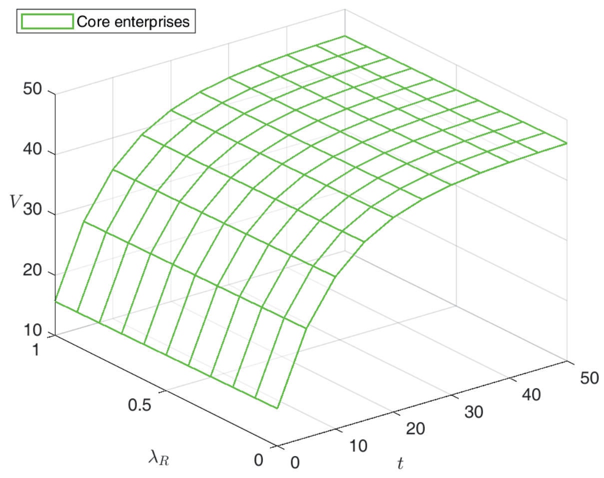


Fig. 9. Effect of ω_R and t on $V_3(I)^*$.



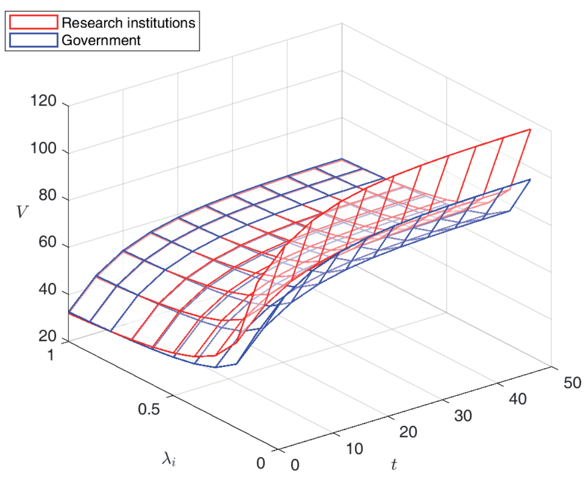


Fig. 10. Effect of λ_R, λ_E, λ_N and t on $V_3(I)^*$.

and development of data security and green technologies, providing financial support for data security-related technologies. At the same time, the government should also improve the urban digital facilities management and operation and maintenance model, clarify the tasks of the relevant responsible subjects, and strengthen the operation and maintenance of digital facilities and the full life cycle management of security protection across fields, levels, departments, and businesses. In addition, the government should take the lead in formulating green standards for industries related to the metaverse, promoting the adoption of low-carbon technologies and renewable energy by enterprises. The government should also establish data security assessment and feedback mechanisms to continuously improve governance levels.

As can be seen from Figs 8 and 9, the impact of the core enterprise's technological innovation capability coefficient and the data security risk assessment capability coefficient on the total benefit of the ecosystem is positive, and the benefit tends to stabilize after increasing substantially over time. A higher technological innovation capability coefficient of core enterprises indicates that these enterprises have invested more resources in the research and development of metaverse-related technologies, continuously introducing new security technologies and solutions, thereby providing robust security protection for data within the metaverse. At the same time, these enterprises can also develop low-power hardware, efficient cooling systems, and energy-saving algorithms, reducing the energy consumption and environmental impact of data infrastructure. Core enterprises with a high data security risk assessment capability coefficient can more accurately identify various data security risks in the metaverse. By conducting comprehensive analyses of the metaverse platform's architecture, data flows, and user behaviors, they can assess potential security vulnerabilities and threats. This enables enterprises to take targeted preventive measures before risks materialize, reducing the likelihood of data security incidents. Even when data security incidents occur, these enterprises can quickly determine the severity and scope of the incidents, providing accurate information support for emergency responses. As a result, resource utilization efficiency is improved, and the environmental costs of data security governance are reduced.

As can be seen from Fig. 10, the cost coefficient of collaborative governance for data safety is negatively correlated with the overall revenue of the ecosystem. Due to the technological innovation and security risk assessment capabilities of core enterprises, core enterprises can develop more advanced encryption algorithms, security protocols, and protection tools to fundamentally improve data security, and thus, the governance costs of the core enterprises have the least impact on the total benefits. Therefore, it is possible to reduce governance costs, increase revenue levels, reduce energy consumption for technology applications, and promote green and sustainable development by adopting data encryption and anonymization technologies, improving mechanisms related to data protection, reducing the risk of data leakage, promoting green technology research and development and innovation, and improving the efficiency of technology application.

Conclusions

This paper incorporates the core enterprise technology innovation capability, data security risk assessment capability, and government incentives into the study of data security collaborative governance issues. Based on differential game theory, the HJB Equation is used to explore the dynamic governance decision-making, benefits, and the development and evolution law of the collaborative governance level of the three-party subjects under different mechanisms, and the coordination of the interests of the three-party subjects is also explored. The study finds:

(1) In the Stackelberg leader–follower game model, the government serves as a guide and supporter to coordinate the behaviors of core enterprises and research institutes through cost sharing and resource integration. This can enhance their willingness to collaborate in governance. The level of growth is equal to the incentive coefficients of the government for core firms and research organizations. However, the game model only improves the willingness of core firms and research organizations to collaborate in governance, and does not affect the governance strategy of the government.

(2) When the three participants cooperate, their respective data security collaborative governance efforts and benefits, as well as the level of collaborative governance and total profits, are better than the Nash non-cooperative game and the Stackelberg master-slave game. Under the three-game mechanisms, the cost of effort and the decay rate of collaborative willingness negatively affect the optimum governance strategy of the participants. The coefficient of collaborative governance capability, the coefficient of technological innovation capability, and the coefficient of data security risk assessment capability positively affect the subject's collaborative governance strategy and optimal returns.

(3) The three game mechanisms have heterogeneous effects on improving the level of collaborative governance. When the initial level of collaborative governance is low, all three mechanisms can pull the level of collaborative governance up. With the increasing level of collaborative governance, the master-slave game under government incentives can drive the innovation ecosystem to realize better collaborative governance. When the level of collaborative governance is high, only the cooperative mechanism can further improve the level of collaborative governance and promote the effectiveness of data security governance.

Recommendations

To enhance the level of collaborative governance of data security within the innovation ecosystem under the metaverse, thereby promoting the stable development of the innovation ecosystem and achieving the dual objectives of data security and green development, based on the aforementioned conclusions, this paper proposes the following recommendations:

(1) Core enterprises should build a security management system that covers the entire life cycle of data, and realize closed-loop management of data security governance through the dual-wheel drive of institutional norms and technical defense. At the institutional level, it is necessary to formulate detailed data operation norms and set up a full-time data security management team to form a virtuous cycle of "identification, disposal, and improvement" through regular audits and dynamic risk assessment. At the technical level, privacy-enhancing technologies should be used to ensure that data is available and invisible, while intelligent security protection systems should be deployed to build an active defense system. In addition, the concept of sustainable development should be integrated into data security practices, and the synergy between security and environmental protection should be realized through modular green data centers and carbon-aware services.

(2) Research institutions should build a multidimensional data security technology system for metaverse scenarios, focusing on breaking through three key dimensions. At the basic technology level, research and development of encryption algorithms, decentralized authentication, and dynamic privacy protection mechanisms adapted to the characteristics of the metaverse should be carried out to provide underlying support for data security. In the intelligent protection dimension, active defense systems integrating artificial intelligence and blockchain technology are developed to realize real-time monitoring of the entire life cycle of data. In the dimension of sustainable development, the concept of green computing is deeply integrated into technology research and development, and focuses on low-energy encryption algorithms to promote synergistic innovation between security technology and environmental friendliness. This technology system can not only provide core support for metaverse data governance and solve key issues such as data authentication and cross-border flow, but also significantly improve the efficiency of security operations and maintenance and reduce management costs through intelligent technology. More importantly, the breakthrough of green security technology realizes the dual goals of security protection and energy saving, and emission reduction, providing an innovative path for building a safe, reliable, efficient, and low-carbon metaverse ecosystem, which is of strategic significance for promoting the high-quality development of the digital economy.

(3) The government should build a perfect metaverse data security governance framework, focusing on promoting institutional construction at three levels. At the level of legal regulation, it is necessary to formulate special metaverse data security management regulations, clearly define data ownership and use norms, and establish a strict disciplinary mechanism for non-compliance. At the level of industry promotion, it is necessary to guide enterprises and scientific research institutions to increase investment in security technology research and development and cultivate the data security industry ecology through a combination of policies such as fiscal and tax incentives and special support. At the level of green development, a green data center certification system should be established, data security energy efficiency standards should be implemented, and policy incentives should be given to enterprises adopting low-carbon technologies. Industrial support policies can stimulate market innovation vigor and accelerate security technology breakthroughs.

The incorporation of green standards into the regulatory framework promotes the formation of a benign interaction between security governance and sustainable development, and provides institutional safeguards for the healthy and orderly development of the metaverse industry.

(4) As an optimal governance paradigm for the development of innovation ecosystems, the core of the cooperative game model lies in the construction of an in-depth synergy mechanism among the government, enterprises, and research institutions. The government should take the lead in formulating green data security standards and low-carbon policies, and set up a special fund to support the research and development of sustainable security technologies. Enterprises need to open up application scenarios and establish energy efficiency assessment mechanisms to accelerate the commercialization of green technologies. Scientific research institutions should pioneer cutting-edge technologies that integrate security and low-carbon principles while providing theoretical and policy support. A tripartite collaborative mechanism should be established to construct a closed-loop system spanning research and development, transformation, and application. In order to maximize synergy, it is proposed to build an integrated governance platform for “data security and green development”, establish a security assessment system that includes carbon emission indicators, and realize real-time sharing of technology dynamics, risk information, and best practices. Through the deep coupling of policy guidance, technological innovation and market application, a new governance pattern with consistent goals, interoperability of resources and synergistic actions will be formed, which will ultimately build a sustainable development ecology that is safe, trustworthy, innovation-led, and environmentally friendly, and provide systematic support for the high-quality development of the digital economy. The deeply integrated collaborative governance model not only enhances the efficacy of data security governance but also facilitates green and low-carbon transition, achieving a synergistic outcome of economic efficiency and environmental sustainability.

Research Limitations and Prospects

Limitations and prospects of this paper: (1) The singularity of the subject's behavioral assumptions. The behavioral assumptions for the three parties of core enterprises, research institutions, and the government are not comprehensive enough, and the decisions of these subjects are affected by a variety of factors, which are only partially taken into account in the model, and subsequent research can take the external competition, social opinion and other factors into account. (2) As there are many participants in the innovation ecosystem, all of them influence the system’s stable equilibrium point. In future research, users and other relevant subjects can be included to construct a differential game model for data security governance involving four-party actors. (3) Collaborative data security governance in the metaverse is a long-term, dynamic process involving multiple stages and levels of decision-making and gaming, and future research can construct multi-stage, multi-level game models. (4) To more intuitively analyze the results of the study and the related inferences, future research can validate them by combining cases about data security governance and green development.

Acknowledgments

I would like to express my gratitude to all those who have assisted me during the research and writing process of this article. In particular, I am deeply grateful to Professor Zou for his encouragement and guidance throughout my writing journey. Additionally, I extend my sincere thanks to the library and electronic reading room for providing a wealth of valuable information that has greatly contributed to my research.

We gratefully acknowledge the financial support from the National Social Science Foundation of China (22BJY135).

Conflict of Interest

The authors declare no conflict of interest.

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