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Evolutionary Path and Sustainable Optimization of an Innovation Ecosystem for a High-Tech Enterprise Based on Empirical Evidence from Hubei Province

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Abstract: This study focuses on the evolutionary path and sustainable optimization of an innovation ecosystem for a high-tech enterprise. To analyze the formation and structure of such an ecosystem, this study applies the Lotka–Volterra model to argue that cooperative symbiosis is an effective path for system evolution. It establishes a system dynamics model to analyze the system feedback mechanism and takes the development of an innovation ecosystem for a high-tech enterprise in Hubei Province as an example to discuss the dynamic factors that affect the system's evolution and to design the sustainable optimization path of the system. The empirical results show that the system's innovation input can only promote the positive effects of system evolution to a certain extent, and that regulatory elements such as policies and infrastructure can impact governance effectiveness and promote system optimization and sustainable development.

Keywords: high-tech enterprise; innovation ecosystem; evolutionary path; simulation; sustainable optimization

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1. Introduction

Deepening specialization and increasing technological complexity make innovation crucial for single enterprises seeking to gain and maintain competitive advantages; these forces also highlight the difficulties individual enterprises face in mastering all the key elements of their given fields [1]. Because of their small-scale, high-income, high-innovation and high-risk natures, high-tech enterprises tend to explore innovation alliances to obtain external information and resources and improve their efficiency and competitiveness through greater division of labor and cooperation [2]. At the same time, the low costs facilitated by information technology and the ease of mergers resulting from competitive globalization catalyze wider innovation cooperation [3], leading individual enterprises to gradually cross industrial boundaries and deeply integrate innovation elements such as human resources, technology, information, and capital with other related parties to form symbiotic relationships, such as competition and cooperation. The organizational structure formed by participating in innovation cooperation has gradually changed; new forms and innovative ecological features have emerged, expanding from simple collaborative innovation to an "innovation ecosystem" that realizes the effective convergence of innovation factors and greater value creation. On this basis, the "innovation ecosystem" can be understood as a community with a perfect cooperative innovation support system, in which each innovation subject carries out collaborative innovation with other subjects by giving play to their own heterogeneity [4]. Therefore, focusing on the innovation ecosystem related to enterprise entities has gradually become a new research hotspot. High-tech enterprises are a special and critical force in promoting regional economic development and upgrades to industrial structures. High-tech enterprise clusters that have high-tech enterprises as their main innovation bod conform to the evolution law of innovation ecosystems. Under the structural framework of the innovation ecosystem of high-tech enterprises, this paper asks the following research questions: Is the interdependence and symbiotic evolution of the innovation ecosystem the evolutionary path of a high-tech enterprise innovation ecosystem? How can enterprises link and integrate their innovation elements, and what are the dynamic factors affecting their effects? How can the optimization and sustainable development of high-tech innovation ecosystems be ensured? The answers to these questions will provide important insights for high-tech enterprises and industrial innovators in China seeking to spearhead development. To explore the above problems and develop a more in-depth theoretical approach for improving the ecological quality of high-tech enterprises, this paper discusses the structural formation of the innovation ecosystem of high-tech enterprises, theoretically analyzes the system's evolutionary path, conducts empirical analysis, and studies the dynamic factors that affect the system evolution and optimization path.

Moore (1990) applied the laws of natural ecology to observe the contemporary economy and envision the economic world of the future, pointing out that future firms should be interconnected and coexist symbiotically; this work marked the emergence of a research paradigm that combines ecosystems and innovation theory [5]. The research content on innovation ecosystems is relatively rich and is mainly composed of two categories. In the first category, researchers apply a structural perspective to study internal relationships, developmental stages, and operational mechanisms based on conceptual definitions and connotative interpretations of innovation ecosystems [6–14]. In the second category, researchers utilize a network perspective to analyze the formation, scales, and other characteristics of such ecosystems [15–18]. The corresponding research model of the innovation ecosystems of high-tech enterprises resembles the standard innovation ecosystem research model in two aspects. First, researchers tend to integrate multiple perspectives as well as micro-, meso-, and macro-elements into a "center of gravity-periphery" analysis framework to conduct research on connotations and mechanisms. Studies applying the idea of natural ecosystem evolution to research on the innovation of high-tech enterprises have found that the path of high-tech enterprise innovation is characterized by ecological genetic variation [19], inspiring researchers to propose the construction of an innovation ecological governance system for high-tech enterprises [20]. The capabilities of enterprises in an innovation ecosystem exist in cooperative inertia, which derives from interactions among members [21] seeking to foster value co-creation [22,23]. The innovation ecosystems of high-tech industries are characterized by four symbiotic evolutionary relationships: competition, mutual benefit, partial benefit, and parasitic coevolution. Therefore, the degree of capability matching among innovation subjects within such systems and their synergistic mechanisms with the external environment are the keys to pushing the innovation ecosystem to continuously develop to a higher level [24]. Within the innovation ecosystem of high-tech enterprises, the central contributor to system evolution is the transfer of production and markets to the field of R&D and technology standards [25]. The functionality of governments and core enterprises affect the sustainability of system evolution [26]; governments serve as the architects of the industrial innovation ecosystem, promoting system evolution in different system development periods through administrative management and financial support [27]. Second, the analysis is based on innovation ecology theory and research, combined with specific cases of innovation in high-tech enterprises to analyze problems and point out some countermeasures. Taking the innovation population as the entry point, we analyze the growth and ecological level of the innovation population in the high-tech industry and find that, overall, it is in a benign rising stage with significant divergent characteristics across regions [28,29]. The enterprises' innovation ecosystem emphasizes the joint participation of enterprises, governments, intermediary structures, scientific research institutes, incubation systems, and other relevant subjects. Taking Shanghai as an example, research has shown that the incentive effect of government R&D investment on the performance of a high-tech enterprise innovation ecosystem is higher than the inhibitory effect in the moderate interval [30], that the innovation environment has a strong positive spatial correlation with innovation efficiency [31], and that industrial efficiency is higher than eco-efficiency [32]. Several problems, including information asymmetry between the government and enterprises, the lack of innovation resources, the competition for resources among innovation subjects, broken chains, contradictions among innovation policies, and the low efficiency of resource allocation [33–36], have given rise to the "system failure" dilemma. Recognizing the above issues, researchers have aimed to optimize the innovation ecosystem from the perspective of innovation governance, including the system stability and resilience [37–39], subject integration, and digital government [40], etc., thus maintaining the sustainability and high quality of enterprise innovation ecosystem development through governance [41,42].

At present, scholars have mostly conducted comprehensive studies on the enterprise innovation system based on static thinking and the macro perspective. However, an innovation ecosystem is a "living" complex system with dynamic and open characteristics, so practical research regarding high-tech enterprises with different attributes should examine them in an individualized manner. In particular, since current regulatory mechanisms for science and technology innovation activities are gradually moving toward science and technology innovation governance, the exploration of the evolutionary path of a high-tech enterprise innovation ecosystem is a realistic problem. Based on innovation theory and symbiosis theory, this paper adopts the "structure-behavior-performance" (SCP) paradigm to open the boundaries of a high-tech enterprise innovation ecosystem from a micro perspective, analyze its formation and structural elements, and demonstrate its internal relationships and evolution path. Based on system theory and synergism theory, this paper analyzes the feedback mechanism of the system from a dynamic perspective, refines the dynamic factors of system evolution through system effect measurement, designs the system optimization scheme, and explores high-quality development countermeasures. The theoretical framework is shown in Figure 1.

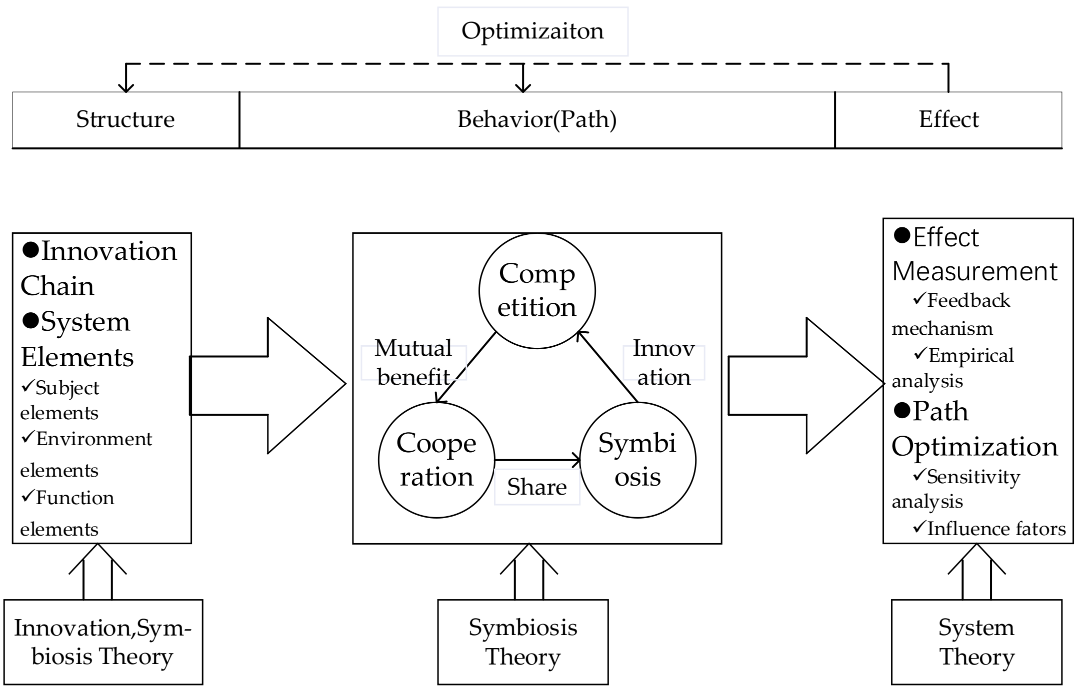

Figure 1. Theoretical framework.

2. Formation and Elements of a High-Tech Enterprise Innovation Ecosystem

2.1. The Formation of the Innovation Chain of a High-Tech Enterprise's Innovation Ecosystem

First, the agglomeration of innovation subjects is a kind of spontaneous behavior. High-tech enterprises join universities, research institutes, and other organizations to engage in cooperative rather than independent innovation. They then form innovation relationship networks and ultimately expand to create innovation ecosystems that encompass entire regions. High-tech enterprises that have strong advantages in technology, capital, and other resources tend to generate correspondingly strong levels of pull to become the core sources of their respective systems, drawing other innovation subjects to them [25–27]. Systems with large numbers of core enterprises and gathering parties have various internal connections that enable them to generate considerable pull, thereby promoting innovation and creating a robust ecosystem. In contrast, when resource disadvantages or weak innovation abilities prevent high-tech enterprises from becoming the cores of their respective systems, other innovation agents are needed to guide and manage the numerous innovation agents. Governments automatically assume responsibility for management because of their managerial attributes. When governments engage in innovation clustering, the innovation activities conducted among high-tech enterprises tend to be more active. In reality, governments seek to develop and enact policies and regulations to enhance high-tech enterprises with weak innovation abilities and accelerate the process of integrating new innovation subjects, thus creating idealized innovation effects.

Second, the formation of innovation chains is a key factor. In innovation chains, which are created simultaneously with high-tech enterprise innovation ecosystems, innovation subjects interact with each other in the form of a chain. High-tech enterprises, governments, universities, and research institutions are the primary innovation subjects, and their varying resources, capabilities, and demands determine the different agglomeration patterns they follow. Therefore, different innovation ecological chains are formed within innovation ecosystems. When high-tech enterprises play the leading party role in innovation ecosystem, they foster mutually beneficial and collaborative relationships between the core enterprises and the partners, and an innovation chain is formed.

2.2. Elements of a High-Tech Enterprise Innovation Ecosystem

As complex systems composed of innovation subjects and their environments, the components of a high-tech enterprise innovation ecosystem are extremely complex, encompassing various innovation subjects such as universities, high-tech enterprises, and research institutes; as well as governments, intermediary service institutions, and various innovative environmental and resource-related elements. In addition, all kinds of innovation talents in the system are the most dynamic elements. As shown in Figure 2, the components of a high-tech enterprise innovation ecosystem can be divided into three categories: first, subject elements, including high-tech enterprises, universities, research institutes, and other innovation organizations and institutions such as intermediary service institutions and organizations serving the innovation process; second, environment elements, including the economic environment, the policy environment, the social and cultural environment, and even the natural environment of innovation and other environmental factors that affect the innovation process and innovation efficiency; and third, function elements. Talents, technology, and capital are key function elements that provide a key platform and power injection for promoting system innovation.

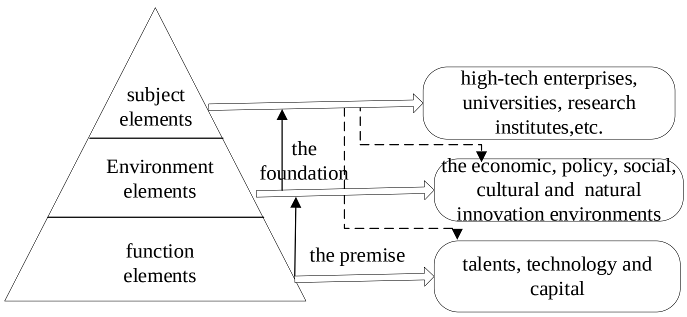

Figure 2. Components of a high-tech enterprise innovation ecosystem.

3. Evolutionary Paths of a High-Tech Enterprise Innovation Ecosystem

According to the symbiosis theory, only by building a sustainable cooperative relationship between related species through resource complementation can these species occupy a favorable position in the group and ultimately promote their continuous evolution [43]. In a high-tech enterprise innovation ecosystem, the innovation subject survives and evolves in the system through competition, sharing, collaboration, and other different modes that realize symbiosis, which is consistent with the evolutionary characteristics of biological populations. An innovation ecosystem emphasizes symbiotic evolution, self-organization, and self-balance among system elements [44]. Systems characterized solely by competition are unstable, while purely cooperative systems lose vitality; reciprocal and competitive relationships make innovation agents interdependent. Reciprocal symbiosis and competition are the basic rules of natural ecosystems and also the basic characteristics of high-tech enterprise innovation ecosystems. The Lotka–Volterra model is among the important models of theoretical ecology [45]. The model analyzes the dynamic processes and behaviors of complex systems under different environments and explores the conditions, statuses, and results of system equilibrium and stability [46–48]. In this paper, we use the Lotka–Volterra model to analyze the interrelationships among innovation populations within a high-tech enterprise innovation ecosystem and thereby reveal its evolutionary form [28]. The relationship is represented by the following model:

$$\frac{dN_i}{dt} = r_i\left(1 - \frac{N_i - \alpha_{ij}N_j + \beta_{ij}N_j}{C_i}\right)N_i \quad (1)$$

where i and j are natural numbers.

Here, N_i denotes the density of high-tech enterprises in the innovation ecosystem, r refers to the growth rate of high-tech enterprises' independent innovation results, and C is the maximum output of innovation subjects when they are independent. Innovative subjects generate two types of co-evolution in the system: competition and cooperative symbiosis. When the relationships between innovation agents are solely competitive, $\alpha_{ij} \geq 0$ denotes the competition factor, and innovation output among innovative populations appears to be mutually suppressed; meanwhile, $\beta_{ij} \geq 0$ indicates that the cooperation coefficients and innovation outputs among innovation populations are mutually reinforcing.

3.1. Competitive Evolution

Condition $\alpha_{12} > 0$, $\alpha_{21} > 0$, $\beta_{12} = \beta_{21} = 0$ is satisfied if two populations of high-tech enterprises in a high-tech enterprise innovation ecosystem are only competing with each other, and the set of equations reflecting this relationship is as follows:

$$\begin{cases} \frac{dN_1}{dt} = r_1\left(1 - \frac{N_1+\alpha_{12}N_2}{C_1}\right)N_1 \\ \frac{dN_2}{dt} = r_2\left(1 - \frac{N_2+\alpha_{21}N_1}{C_2}\right)N_2 \end{cases} \quad (2)$$

The equation has four equilibrium points; these are $E_1(0,\ 0)$, $E_2(0,\ C_2)$, $E_3(C_1,\ 0)$, and $E_4\left(\frac{C_1-\alpha_{12}C_2}{1-\alpha_{12}\alpha_{21}},\ \frac{C_2-\alpha_{21}C_1}{1-\alpha_{12}\alpha_{21}}\right)$. Figure 3 shows the evolutionary trend L_1 and L_2 among populations of high-tech enterprises in this purely competitive state. The specific situation can be analyzed in the following respects.

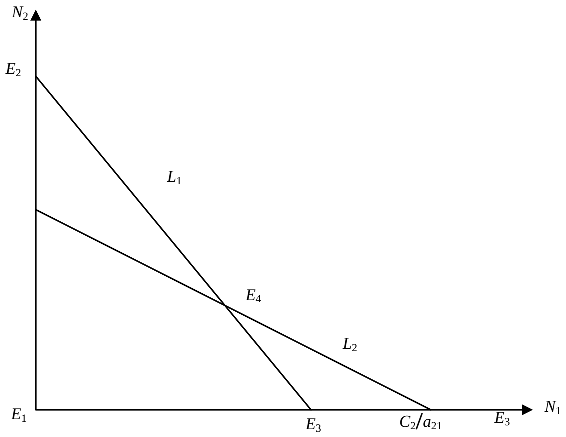

Figure 3. Competitive evolution of innovation populations of high-tech enterprises.

Conditions $\alpha_{12}\alpha_{21} < 1$ and $\alpha_{12} < C_1/C_2 < 1/\alpha_{21}$ of $E_4\left(\frac{C_1-\alpha_{12}C_2}{1-\alpha_{12}\alpha_{21}}, \frac{C_2-\alpha_{21}C_1}{1-\alpha_{12}\alpha_{21}}\right)$ represent a stable solution; the two populations eventually converge at the equilibrium point. However, the outputs of both populations do not reach the highest possible levels, and the steady state of the system changes with changes in the system parameters. When $\alpha_{12} > C_1/C_2$ and $\alpha_{21} > C_2/C_1$ are satisfied, a stable answer appears; these are $E_2(0,\ C_2)$ and $E_3(C_1,\ 0)$. The results show that high-tech enterprise populations with higher innovation outputs win the competition. When $\alpha_{12} < C_1/C_2$ and $\alpha_{21} < C_2/C_1$ are satisfied, and when $t \to +\infty$, $E_3(C_1,\ 0)$ is a stable answer. The two lines L_1, L_2 do not intersect when $t \in (0, +\infty)$; this indicates that as competition intensifies, one side generates more innovation outputs, and innovation resources gradually shift to the side with more innovation outputs, giving that side more and more competitive advantages while the innovation outputs of the other side gradually decrease to zero and eventually disappear. Thus, the key to winning the competition between high-tech enterprise populations is to increase both innovation output values and innovation generation growth rates.

3.2. Cooperative Evolution

In the form of competition evolution, if innovation subjects in one party eventually exit the system due to their gradual decrease in output, the system will return to its original form, and other innovation subjects will undergo a negative cycle due to the decrease in resources that reduces their output rate; this is what "rational" subjects do not want to see. Therefore, both parties will adopt positive cooperation intentions and strategies to improve system efficiency [46–48]. If two populations of high-tech enterprises adopt a cooperative strategy in competition to enhance innovation output efficiency (if $\alpha_{12} = \alpha_{21} = 0,\ \beta_{12} \neq 0,\ \beta_{21} \neq 0$), the corresponding system of relational equations is as follows:

$$\begin{cases} \frac{dN_1}{dt} = r_1\left(1 - \frac{N_1-\beta_{12}N_2}{C_1}\right)N_1 \\ \frac{dN_2}{dt} = r_2\left(1 - \frac{N_2-\beta_{21}N_1}{C_2}\right)N_2 \end{cases} \quad (3)$$

Figure 4 shows the evolutionary trend among populations of high-tech enterprises. The dash-line arrow also shows the equilibrium relationship between the two innovation populations L_1 and L_2 with the change of high-tech enterprise density N_1 and N_2 in the innovation ecosystem. When $\beta_{12}\beta_{21} < 1$, the answer to this equation is four equilibrium points. These are $E_1{}'(0,0)$, $E_2{}'(0, C_2{}')$, $E_3{}'(C_1{}', 0)$, and $E_4{}'\left(\frac{C_1{}'+\beta_{12}C_2{}'}{1-\beta_{12}\beta_{21}}, \frac{C_2{}'+\beta_{21}C_1{}'}{1-\beta_{12}\beta_{21}}\right)$. As Figure 3 shows, when $(\alpha_{12}-\beta_{12})(\alpha_{21}-\beta_{21}) < 1$, $E_4{}'\left(\frac{C_1{}'+\beta_{12}C_2{}'}{1-\beta_{12}\beta_{21}}, \frac{C_2{}'+\beta_{21}C_1{}'}{1-\beta_{12}\beta_{21}}\right)$ is the stable solution of the system, and the innovation populations reach equilibrium; although neither population reaches maximum output via cooperation, when $t \to +\infty$, the two innovation populations will spiral between two straight lines, signaling a symbiotic and co-prosperous situation. Meanwhile, condition $C_1{}' > C_1,\ C_2{}' > C_2$ is also satisfied. This indicates that the reciprocal effect of cooperation between the two innovation populations is greater than the inhibitory effect of competition, and cooperative evolution is the driving force for the development of innovation populations. Competition motivates innovation populations to innovate, while cooperation expands each innovation population's development space. In sum, coexistence and symbiosis are the driving forces of innovation ecosystems, combining to form an effective mode of system operation.

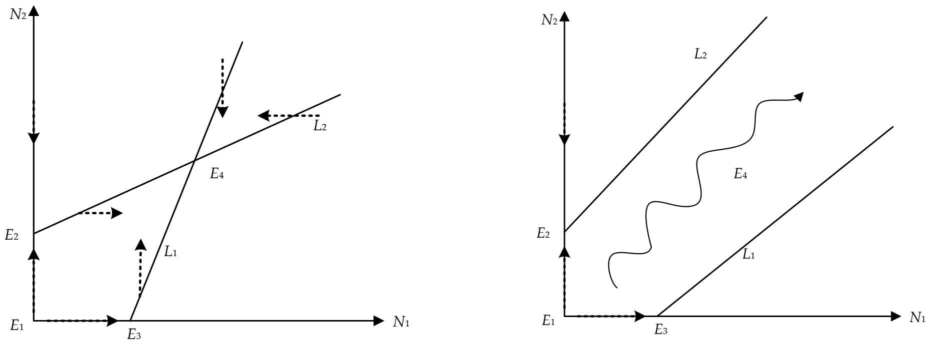

Figure 4. Cooperative evolution of innovation populations of high-tech enterprises.

4. Optimization of the Evolutionary Path of a High-Tech Enterprise Innovation Ecosystem

4.1. Measurement of the Evolution Effect of a High-Tech Enterprise Innovation Ecosystem

Together, cooperation, reciprocity, and symbiosis constitute the ideal evolutionary mode for a high-tech enterprise innovation ecosystem, enabling innovation subjects and innovation populations to achieve value co-creation within these systems. To optimize the evolutionary paths of these ecosystems and improve their innovation outputs, it is necessary to evaluate the effects of an innovation ecosystem's evolution and refine the dynamic factors of system optimization. Recognizing this, this section analyzes the feedback mechanism of a high-tech enterprise innovation ecosystem, empirically analyzes the impact of a high-tech enterprise innovation ecosystem in Hubei Province, refines the key driving factors, and designs the optimization path of system evolution.

4.1.1. Research Method

Analyzing economic systems with long-term developmental inertia requires the consideration of system dynamics. High-tech enterprise innovation ecosystems fall into the socio-economic system category; they are dynamic evolutionary systems composed of many interconnected and interacting innovation units. High-tech enterprises, governments, research institutions, and other innovation subjects are the main subjects of their activities, which have the characteristics of non-linearity, complexity, integration, openness, and dynamic interaction, amongst others. Several variables influence and constrain the operation of these systems; these variables function as self-organizing forces under the guidance and impetus of sequential parameters, forming multiple feedback loops under the constraints of control parameters and returning positive and negative feedback to the system inputs to influence the systems' week-by-week functions. Thus, the basic conditions of a high-tech enterprise innovation ecosystem make the system dynamics method—a very effective tool for evaluating system effects—an appropriate method for analyzing them.

4.1.2. Research Design

(1) System Boundary and Condition Assumptions

Based on the structure of a high-tech enterprise innovation ecosystem and the perspective of system dynamics, the system is divided into two subsystems, namely, the subject subsystem and the regulator subsystem. The main performance of the subject subsystem is that innovation subjects with high-tech enterprises as their core eventually realize product and technology innovation through exchange and collaboration. The regulator subsystem refers to the external factors acting in the system, including political, economic, financial, technological, infrastructural, and other environmental factors that influence the behavior of the subjects and determine the direction of system operation. The regulator subsystem internally regulates the behavior of subjects and externally regulates market behavior and the environment to stabilize and balance the system's state.

In applying the method of system dynamics to evaluate a high-tech enterprise innovation ecosystem, we made the following assumptions: that the system operates normally without unpredictable contingencies, such as major policy changes and natural disasters; and that the innovation subjects' inputs all have a positive impact on the system's outputs. To account for the system's R&D outcome outputs, we counted the collaborative outcomes of innovation subjects once; to simplify the simulation, the evolutionary model does not consider the time delay problem.

(2) Causality of a High-Tech Enterprise Innovation Ecosystem

Under policy, system, infrastructure construction, and other regulator subsystem guarantees, innovation subjects do the following: invest human, material, and financial resources; collaborate with other innovation subjects to innovate; continuously develop new products; and obtain expected returns. The system's positive development promotes the development of the regional economy, thereby contributing to the optimization of the environment and establishing a virtuous circle. At the same time and on the contrary, a vicious circle also forms. In such an innovation ecosystem, the following cause–effect loops exist:

① The behavior of high-tech enterprises promotes the development of the system loop. High-tech enterprises provide new products or services through technological innovation, realize their own economic benefits, and influence each other to deepen cooperation with other innovation subjects and promote the development of the innovation ecosystem.

② Other innovation subjects in the system promote the system development loop. Non-high-tech enterprise innovation subjects promote a high-tech enterprise innovation by making policies, enacting institutional measures, optimizing a flexible and convenient innovation environment, improving infrastructure, etc., thereby promoting the innovation ecosystem's development.

③ The innovation ecosystem and social economy promote one another's development loops. Socioeconomic growth and structural optimization are important factors that influence and promote ecosystem evolution. Economic growth provides a good operating basis for system development, facilitating the continuous expansion of high-tech industries, increasing efficiency, and boosting revenue. The innovation ecosystem's development bolsters regional and local economies and continuously optimizes the economic structure.

We use the above analysis as the basis for the causality diagram of a high-tech enterprise innovation ecosystem shown in Figure 5.

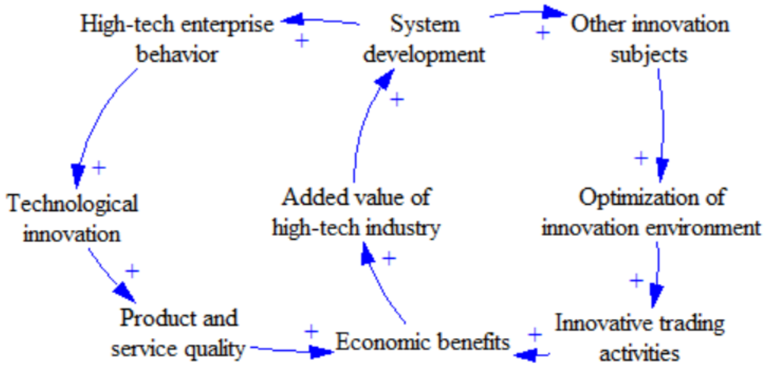

Figure 5. Cause-and-effect diagram of high-tech enterprise innovation ecosystem.

(3) Feedback Mechanism of a High-Tech Enterprise Innovation Ecosystem

A high-tech enterprise innovation ecosystem promotes its own continuous development through the "innovation resources input → innovation guarantee operation → innovation benefit output" cycle. In this study, we analyzed the following three dimensions of the system effects:

① The ecosystem's main body synergy and value creation. The development demands of high-tech enterprises and other innovation subjects are sources of motivation, synergy, and collaboration among innovation clusters within the system. These are the bases and premises of the system's development, and the quality of these relationships determines the depth of evolution. Based on the goal and result of value creation, the system can overcome the "locking" cluster capacity dilemma; promote the innovation system's supersession; obtain the latest information, knowledge, and other innovation resources; and keep the system dynamic.

② High-tech enterprise innovation cluster resources guarantee. Innovation resources are the core prerequisite for the clustering of innovation subjects and the formation of an innovation chain. Core enterprises leverage their resource advantages—including technologies, talent, and capabilities—to attract other enterprises to cooperate with them. Meanwhile, support from the external environment, such as government funding, policy support, and sound foundation implementation, promotes the formation of innovation clusters.

③ High-tech enterprise innovation ecosystem output. The innovation ecosystem's effects reflect the strength of the innovation clusters' innovation capacities, which are directly reflected in the outputs of the innovation ecosystem's innovation activities.

We clarified the internal and external dynamic factors and development logic of the system by conducting a causality analysis. The system used a total of four indicators—namely, the high-tech industry's output value, the number of high-tech enterprises, the number of people employed bt high-tech enterprises, and the accumulated amount of intellectual property rights—as horizontal variables and established a system dynamics model with a total of 35 variables designed to detect the evolutionary trend. Figure 6 shows the system power flow diagram. From the analysis of causality and feedback mechanism, it was found that if the resource input of education resources, talent introduction, R&D costs, etc. in the subject subsystem is changed, and the financial environment, business policies, scientific research infrastructure supply and other ecological environment elements in the regulator subsystem are adjusted, the values of horizontal variables will fluctuate, leading to changes in the system output and evolution state.

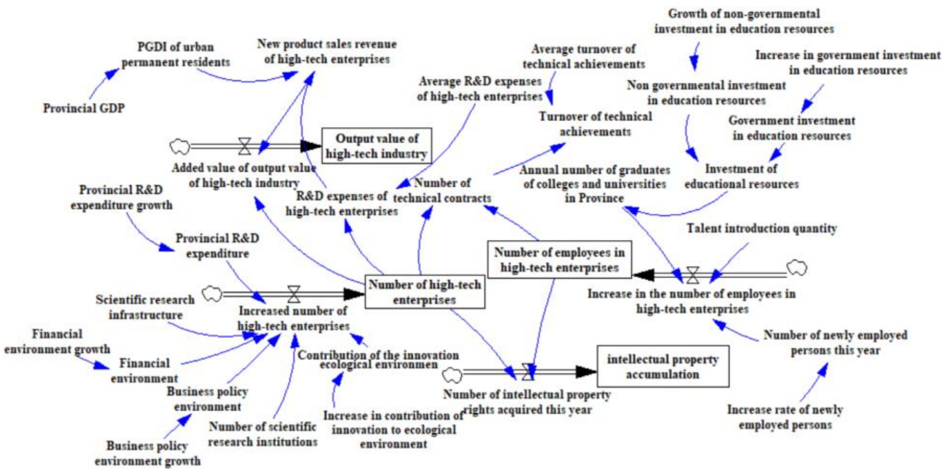

Figure 6. Flow chart of high-tech enterprise innovation ecosystem.

(4) Empirical Evidence from Hubei Province

According to the research design in the previous content, a case study was carried out to design the start time, end time, and step size of the simulation. The index variable values were brought into the system dynamics model and debugged repeatedly. We verified the authenticity of the simulation results to ensure the authenticity and accuracy of the content and model. A sensitivity test was conducted to obtain the key factors affecting the model and to lay a foundation for further policy design. The relevant index values of high-tech enterprises in Hubei Province from 2011 to 2020 were taken as the benchmark data, and the simulation was run with Vensim software. We obtained the model statistics from the Hubei Provincial Statistical Yearbook (2011–2020) and the official websites of the Hubei Provincial Department of Science and Technology and Hubei Provincial Bureau of Statistics. We verified the accuracy of the model, and the analysis showed that the model passed the historical test; the systematic error was controlled within 5%, indicating that it had a high level of accuracy and could reflect the real situation objectively and reasonably.

The simulation results in Figure 7 show the evolutionary trajectory of a high-tech enterprise innovation ecosystem in Hubei province for a total of 21 years from 2011 to 2031, selecting "high-tech industry output value", "high-tech enterprise R&D cost", "technology achievement turnover", and "innovation ecosystem contribution" to observe the development of the system dynamics. With the joint action of the subject subsystem and the regulator subsystem, the four indicators have gradually increased, with a relatively consistent change trend. The change in eco-environmental innovation contributions acts on output indicators, including the output value of the high-tech industry and the turnover of technological achievements, and has a specific lagging impact; the turnover trend for technological achievement is especially consistent with this characteristic. Notably, the R&D expenses of high-tech enterprises decreased year-by-year, reaching an inflection point from 2015 to 2018, and then increasing year-by-year thereafter; this is a key factor influencing the rising output indicators. Examining the change in the "high-tech enterprise R&D cost" indicator, as our system power flow diagram shows, we found that the "average R&D cost of high-tech enterprises" influenced this indicator, which historically showed a decreasing year-by-year trend that correlated to the high growth rate of high-tech enterprises in recent years. This is related to the high growth rate of the number of high-tech enterprises in recent years.

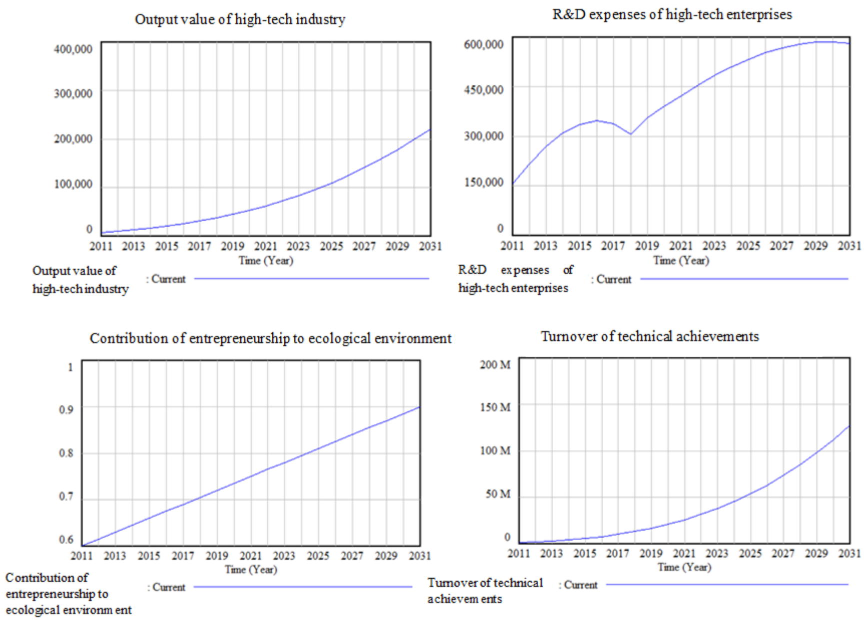

Figure 7. Simulation results of a high-tech enterprise innovation ecosystem.

4.2. Optimization Design of Evolutionary Path of a High-Tech Nterprise Innovation Ecosystem

The sensitivity analysis of the system dynamics model in the case was carried out, and different indicators were selected to adjust their variable values. After several experiments, it was found that changing the input indicators in the subject subsystem and the environmental indicators in the regulator subsystem would have a significant positive effect on the system's results. Therefore, in the optimization design of the evolutionary path, "R&D cost of high-tech enterprises" and environmental indicators were selected for calculation experiments.

4.2.1. Increase Investment in System Innovation

In this scheme, we examined the impact of changes in inputs to the subject subsystem on the system outputs. We determined the system output value by adjusting the rate of change in the high-tech enterprise R&D costs. As shown in Figure 8, the rate of decrease in the "high-tech enterprise R&D cost" indicator slowed down, and we assumed the increase in the "high-tech enterprise R&D cost" indicator to be 10% (current1 curve). The "high-tech industry output value" indicator value increased slowly compared to the original simulation value (current curve); the "high-tech enterprise R&D cost" indicator value increased by by 20% (current2 curve), and the "high-tech industry output value" indicator value increased by 20% (current curve). Meanwhile, the "high-tech industry output value" index value did not differ much from the previous simulation. This indicated that the main subsystem did not have a significant impact on system output when innovation subjects' inputs were increased to a certain degree.

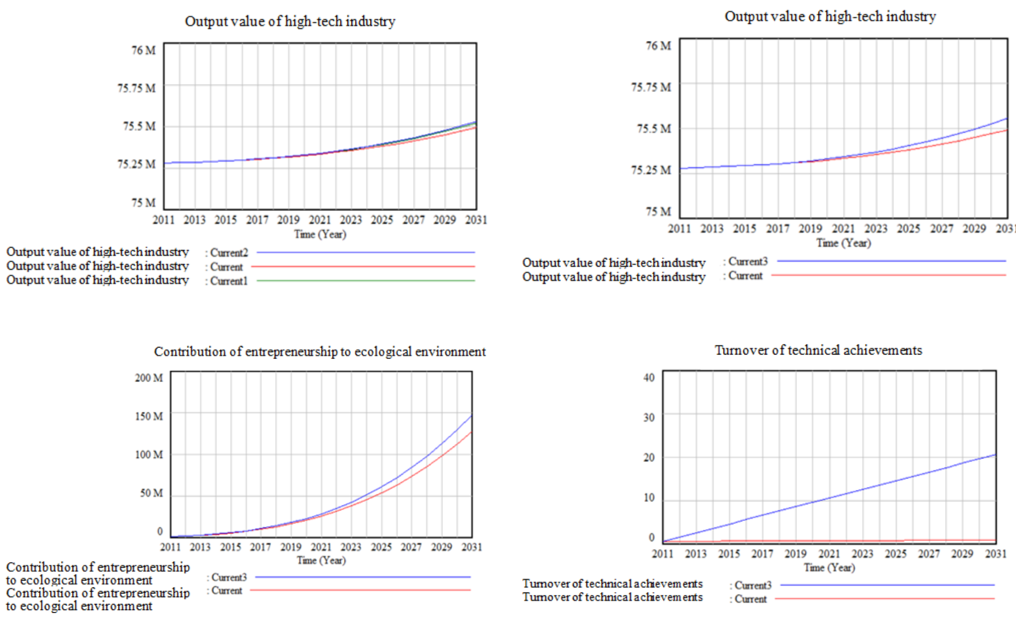

Figure 8. Simulation results of high-tech enterprise innovation ecosystem.

4.2.2. Optimizing the Innovation Ecological Environment

We also examined the impact of changes in the regulator subsystem indicators on system outputs. We selected the "research infrastructure", "increase in business policy environment", and "increase in innovation ecosystem" indicators for policy experiments. Figure 8 shows the system output variables trend after increasing the index values by 10% and running them through the software. The Current curve shows the variables in the original state, and the Current3 curve shows the changes in the relevant variables following the 10% increase in the indicator value. We found that after increasing the value of eco-environmental contributions, the relevant output variables and action factor values increased accordingly. In addition, the analysis showed that increasing the ecological environment contribution input had a multiplier effect on the innovation input contribution.

The effect of the eco-environmental contribution coefficient on the development of the innovation ecosystem in Hubei Province was positive and obvious; specifically, it could improve the innovation environment, increase the value of eco-environmental contributions, and effectively promote the development of a high-tech enterprise innovation ecosystem in Hubei Province through programs and means such as increasing fiscal expenditure, strengthening the development of research infrastructure, optimizing industrial structures, and continuously implementing preferential policies.

5. Conclusions

Focusing on the evolutionary path of a high-tech enterprise innovation ecosystem based on system theory, innovation theory, and ecological symbiosis theory, this paper analyzed the formation and components of a high-tech enterprise innovation ecosystem. We constructed a symbiosis model to explore the interrelationships among innovation populations in innovation ecosystems from a dynamic perspective and argued that only by increasing the innovation output and the growth rate of innovation production could innovative enterprises improve the probability of winning the competition. At the same time, the cooperative reciprocity effect between two innovation populations was greater than the competitive inhibition effect, and the cooperative evolution was the effective path of the system evolution. Competition stimulates the innovation populations' motivation to innovate; cooperation, on the other hand, expands the development space of each innovation population. We analyzed the system feedback mechanism, took the development of a high-tech enterprise innovation ecosystem in Hubei Province as an example to measure the effect, refined the key factors of system development and evolution, and designed a sustainable optimization path of the system. Our simulation showed that although the main innovation body input had a positive effect on the innovation ecosystem's evolution, the effect of continuous input gradually decreased. The regulator subsystem elements in the system—including government, policy, and infrastructure—need to play a governance role, adjust the system equilibrium state, focus on building mutually beneficial symbiotic relationships to promote value co-creation, and help the innovation ecosystem continuously optimize its competitive advantage. On this basis, an optimization scheme of system evolutionary path was proposed to increase system innovation input and optimize innovation ecological environment.

Our evaluation of data related to the innovation system effect in Hubei Province showed that high-tech enterprises in Hubei Province were following a positive development trend with robust policy support, institutional assistance, and continuous optimization of the innovation ecosystem. However, the simulation analysis results also revealed some problems, including insufficient innovation investment and low linkage vitality among innovation subjects. To sustain the vigor and vitality of the regional high-tech enterprise innovation ecosystem, the system must be optimized through science and technology innovation governance. Science and technology innovation governance is inseparable from resource investment and mechanism and policy innovations. To some extent, policy innovation may be a norm in the innovation ecosystem. In the context of progressive reform, mechanism and policy innovation are often the core drivers of institutional reform.

In addition to increasing innovation investment, the innovation ecosystem support system must be strengthened. Since high-tech enterprises operate in high-investment and high-risk industries, their creation and development require a large amount of capital; this means the development of high-tech enterprises in China is severely constrained by capital. According to the case data, although total innovation investment of high-tech enterprises has been increasing, R&D expenditures have followed a slowing trend year-by-year. In addition, a horizontal comparison revealed that provincial expenditures for science and technology are currently much lower than enterprise R&D investment expenditures, and high-tech enterprises' innovation investment comes mainly from self-financing and is inhibited by certain external environmental restrictions that greatly hinder the innovation enthusiasm of high-tech enterprise innovation ecological subjects. Without appropriate levels of investment, enterprises cannot become true innovation subjects. The government should establish a coordination mechanism to promote the formation of government investment as a guide, enterprise investment as the main body, and financial and venture capital for support, while actively seeking to attract social capital and the introduction of foreign investment.

Meanwhile, our analysis highlighted the importance of strengthening policy support and consolidating the foundation of the entrepreneurship and innovation ecosystem. At present, policies related to high-tech enterprises in the case area are relatively unitary and narrow in coverage. Policy innovation is the main means and an important lever of scientific and technological governance. Our findings suggest that policymakers should seek to strengthen the policy support system, design targeted support policies based on the development characteristics and laws governing high-tech enterprises and contribute to both cultivation and development. Starting with the identification of high-tech enterprises, they should issue a special work plan for the cultivation of high-tech start-ups and establish a one-stop incubation, cultivation, and identification working mechanism to facilitate the upper-echelon growth of high-tech enterprises. They should also set up a platform to foster the rapid growth of high-tech enterprises in terms of finance, taxation, trade, talent, and platform construction to establish an innovation ecological policy chain and thereby build a rapid promotion channel for the growth of high-tech enterprises at the policy level.

Finally, our findings underscore the need to deepen the integration of factors and promote linkage development in regional innovation ecology. Policymakers should seek to accomplish this by formulating policies and systems; creating innovative environments; providing resources and other means of innovation; attracting talent; increasing investment, technology research, and development; and imposing other specific measures that would provide opportunities for the innovative development of high-tech enterprises. At the same time, they should also seek to introduce competition from the outside world to strengthen external pressure or attraction and thereby reduce the “path dependence” of high-tech enterprise innovation clusters on past innovation achievements whilst cultivating sustainable innovation power.

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