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# Research on the Knowledge-Sharing Incentive of the Cross-Boundary Alliance Symbiotic System

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**Abstract:** The rise of the cross-boundary alliance as a new organizational model profoundly affects innovation development. The incentive mode of knowledge-sharing among cross-boundary alliance members from the perspective of symbiosis is the key to improving the efficiency of knowledge-sharing and promoting the alliance's sustainable development. Due to the interdisciplinary nature of knowledge and information asymmetry among alliance members, knowledge-sharing is prone to opportunistic behavior, which greatly impacts cross- boundary innovation cooperation. The symbiotic system of the cross-boundary alliance is constructed based on the analysis of symbiosis among alliance members to solve these problems. In this research study, the principal–agent theory is used to describe the expected benefits and the related constraints of knowledge-sharing partners. Moreover, an incentive model of knowledge-sharing in the cross-boundary alliance is established. By solving the model, the agent's sharing intention and the principal's reward incentive coefficient are obtained, which provide a theoretical basis for the formulation of the optimal incentive scheme of knowledge-sharing in the alliance. The results show that the knowledge potential difference, knowledge transmission efficiency, knowledge transformation, innovation effort, and the symbiotic environment will directly affect the knowledge transfer level of the alliance. In this research study, a theoretical research framework of the cross-boundary alliance symbiotic system linked by knowledge-sharing is constructed. The incentive model of knowledge-sharing is established especially on the basis of fully considering the internal and external factors of knowledge-sharing. This research study has provided some innovation in the theoretical system and method improvement, and has guaranteed the efficient integration, utilization, and innovation of knowledge resources in the cross-boundary alliance.

**Keywords:** cross-boundary alliance; symbiotic system; knowledge-sharing incentive; principal agent

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## 1. Introduction

Knowledge-sharing arrangements are an essential part of the innovation process as they help enterprises acquire technological capabilities, shorten development time, and spread risk and cost [1]. With the deep integration of the new generation of information technology and the real economy, the collaborative cooperation between organizations across industrial boundaries has become a new normal of business [2]. More and more enterprises are no longer limited to using their existing technology and knowledge but by participating in cross-field, cross-industry, and cross-department cooperation, are able to establish cross-boundary alliances [3]. The construction of cross-boundary alliances can accelerate heterogeneous knowledge-sharing and transfer activities, as well as promote new products and services to realize value added [4]. The cross-boundary alliance can be regarded as having a mutually beneficial and symbiotic organizational form [5]. Under the joint action of collaborative symbiosis among alliance members, alliance incentives, and guidance measures [6], the continuous sharing of alliance knowledge will directly affect the cross-boundary innovation efficiency.

Knowledge is the basis of innovation and knowledge-sharing, integration, and absorption are the paths for organizations to realize innovation [7]. At present, the related literature on alliance knowledge-sharing focuses on the evolution path of alliance knowledge-sharing [8], sharing rules [9,10], influencing factors of sharing behavior [11,12], and the knowledge-sharing mode from the perspective of a social network [13,14]. It is found that knowledge-sharing has a noticeable promoting effect on the innovation performance of alliances [15–17]. The efficiency of knowledge-sharing is determined by the elements included in the process of knowledge-sharing, such as the characteristics of the shared knowledge, the participants involved, the purpose and barriers, and the means through which knowledge is shared [18,19]. Furthermore, the lack of contact and trust among alliance members and the interdisciplinarity of the knowledge among alliance members are the main reasons that hinder knowledge-sharing [20–24]. Therefore, it is very necessary to establish an effective incentive mechanism for knowledge-sharing.

Incentive theory has universal adaptability in economic management activities. The purpose of motivation is to seek an optimal contract to promote the optimal state of Pareto among economic subjects. At present, research on the knowledge-sharing incentive mechanism has attracted many scholars. Some scholars use game theory and other methods to study the incentive model of knowledge-sharing within enterprises, between enterprises, and between customers and enterprise R&D personnel based on knowledge structure, knowledge type, and other factors [25,26]. Kong established an evolutionary game model of knowledge-sharing behavior in a cluster innovation network based on evolutionary game theory [27]. Arora et al. developed a model of knowledge-sharing in alliances and alliance portfolios [28]. Based on the game theory, Xiong et al. constructed the incentive model of innovation failure knowledge-sharing in virtual research organizations considering the risk aversion degree of members and the negative effect of a fault-tolerance environment [29]. Ma et al. proposed the dynamic incentive model for knowledge-sharing in the Design-Build joint ventures under three types of contracts: the no cost-sharing contract, cost-sharing contract, and centralized decision-making contract [30]. Through the above research, it can be found that the incentive mechanism is an essential factor that promotes the smooth progress of organizational knowledge-sharing activities and a practical external incentive mechanism can significantly improve the probability of enterprises behaving honestly in cooperation-sharing [31]. The research on the knowledge-sharing incentive mechanism of cross-boundary alliances can effectively increase the willingness of alliance members to share knowledge, accelerate the knowledge flow in cross-boundary partnerships, and provide a guarantee for cross-boundary cooperation among members. The effective incentive mechanism for knowledge-sharing can promote the formation of symbiotic relations among cross-boundary alliances. The good symbiosis environment also has the ideal incentive effect on the knowledge-sharing activities among the members of the alliance and it encourages the co-evolution of the symbiosis mode among the members of the cross-boundary alliance.

The symbiosis theory originated from the field of ecology. The symbiosis relationship originally refers to a kind of dependence relationship in which the organisms in the ecosystem gradually move towards unity to adapt to the complex and changeable environment. Many scholars have applied it to sociology and economics in recent years, which provides an analytical perspective for the study of knowledge-sharing in cross-boundary alliances [32]. The European Union highlights industrial symbiosis as a methodology that stimulates industries to become more sustainable [33]. Grant et al. proposed an industrial symbiosis process model that describes the development of industrial symbiosis scenarios [34]. Other scholars use the symbiotic sustainability model to study the relationship between different types of organizations in cross-boundary cooperation [35]. Therefore, based on the theory of ecological symbiosis, it is necessary to construct a knowledge-sharing game model in the environment of a cross-boundary alliance symbiosis system and deeply explore the main factors that affect the incentives of alliance knowledge-sharing. This study

plays a positive role in optimizing the development environment of the alliance symbiosis system and accelerating the further integration and innovation of alliance knowledge.

Mirroring this sequence are the following relevant research questions: (1) How to construct a cooperative symbiosis system to analyze knowledge-sharing activities among members of a cross-boundary alliance? (2) How to effectively promote knowledge-sharing among alliance members through knowledge management? [36] (3) How to design the incentive mechanism of knowledge-sharing to balance the benefits and risks of symbiotic partners? These are the key issues in improving the heterogeneous knowledge resource allocation efficiency among alliance members and ensuring the alliance's sustainable development and stable operation

Through the analysis of the research status of the knowledge-sharing incentive, it can be found that scholars have done more research on alliance knowledge-sharing. Still, the research on knowledge-sharing issues for the new organization of cross-boundary alliances needs to be further studied. Especially under the background of integrating the organizational knowledge management theory and ecological theory, building a cross-boundary alliance collaborative symbiosis system to analyze the knowledge-sharing activities among alliance members will be a core issue to improve the efficiency of heterogeneous knowledge resource allocation effectively. In addition, how to design a knowledge-sharing incentive mechanism that can reflect the difference of the knowledge potential and the elements of the ecological environment inside and outside the alliance to balance the benefits and risks of alliance symbiosis will be another crucial problem to be solved. The above issues will provide a guarantee for the sustainable development and stable operation of the alliance. Therefore, combined with the characteristics of the cross-boundary alliance and symbiosis theory, this research study takes the incentive problem of knowledge-sharing in the collaborative innovation of cross-boundary alliance as the research object and constructs the knowledge resource symbiosis system of cross-boundary alliances based on the collaborative symbiosis relationship among alliance members. In the alliance symbiosis environment, this paper analyzes the principal–agent relationship in the knowledge-sharing process of the alliance. The research study establishes a knowledge-sharing incentive model of cross-boundary alliances based on the principal–agent theory and analyzes the model's results to maximize the symbiotic benefits of knowledge resources. The research results enrich the management theory of the knowledge resource symbiosis system of the cross-boundary alliance, provide an effective solution for accelerating alliance knowledge-sharing activities, and improve the efficiency of knowledge resource utilization.

The remainder of this paper is structured as follows. Section 2 builds the conceptual model of the cross-boundary alliance symbiotic system and analyzes the principal–agent relationship of knowledge-sharing in the cross-boundary alliance symbiotic system. Model assumptions, notations, and formulations are developed in Section 3. Numerical simulations and discussions are presented in Section 4. Finally, some conclusions, limitations, and prospects are provided in Section 5.

## 2. Theoretical Framework

### *2.1. The Construction of the Symbiotic System Conceptual Model of Cross-Boundary Alliances*

A cross-boundary alliance is a dynamic alliance formed with the goal of (1) cooperation and innovation among organizations; (2) creating the basis of a comprehensive utilization of resources; and (3) creating the link of mutual benefit-sharing of cross-boundary knowledge. From an ecology perspective, it is essentially a symbiotic system [37] and the symbiotic relationship in the system is the basis for the cross-boundary flow of knowledge. The alliance members divide the work based on their respective niche in the system and use the symbiosis relationship of the system to share knowledge and co-innovate [38]. The cross-boundary alliance symbiosis system is comprised of four basic elements: the symbiosis unit, symbiosis matrix, symbiosis environment, and symbiosis interface. The elements' interaction relationships are shown in Figure 1. The symbiotic factors and their interaction affect the operation and development of the symbiotic system of the cross-boundary alliance.

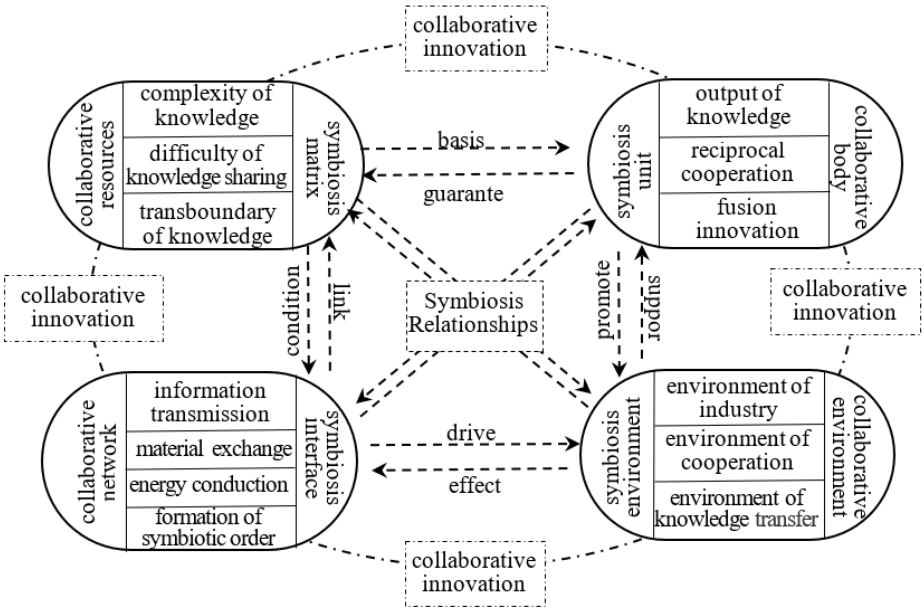


**Figure 1.** Cross-boundary alliance symbiotic system conceptual model.

The symbiotic unit is the basic unit of a symbiotic system [39], which is also the main element of knowledge-sharing among members of a cross-boundary alliance. In the process of knowledge-sharing in cross-boundary alliances, symbiotic units can be divided into knowledge spillover and knowledge demander. Knowledge spillovers are the members of the alliance who provide knowledge. The knowledge demander completes the transformation and application of knowledge by learning and absorbing the knowledge and technology supplied by the knowledge spillover.

The symbiotic matrix refers to the cross-boundary knowledge and other basic resources flowing among symbiotic units. The differences in resources owned by cross-boundary alliance members led to knowledge-sharing activities in the symbiotic system. The fusion of the symbiotic matrix makes two or more symbiotic units in different industries become interdependent symbiotic partners and complete the evolution of the symbiotic system in mutual motivation.

The symbiotic environment is the internal and external factors for the survival of a symbiotic system [40]. The symbiotic environment in the symbiotic system of the cross-boundary alliance is not only affected by the cooperative relationship within the alliance but also influenced and restricted by external factors. The internal environment includes long-term and stable cooperation relationships of mutual trust, benefit-sharing, and common development between knowledge spillovers and knowledge demanders within the alliance. The external environment includes the natural environment, industrial environment, social environment, technical environment, and other external factors outside the alliance.

The symbiosis interface refers to the contact mode and contact mechanism of cross-boundary alliance members to form symbiosis relationships and symbiosis behaviors under the knowledge resources' symbiosis environment. It is also the channel and medium for cross-boundary alliance members to share knowledge and is the basis for forming and developing symbiotic relationships.

The collaboration between symbiotic units promotes the healthy development of a symbiotic environment. With the continuous development of the symbiotic environment, symbiotic units create value on the symbiotic interface through the cross-boundary flow of the symbiotic matrix. This makes the symbiotic relationship and symbiotic effect among symbiotic units appear, enables the sustainable reuse and innovation of alliance knowledge resources, and finally makes the alliance competitive strength continue to improve.

The symbiotic system of the cross-boundary alliance has certain risks in the process of development. Factors such as geographical location, organizational culture, the cooperation

mode, and the benefit distribution mode among symbiotic units directly affect the stability and continuous evolution of the symbiotic system of the cross-boundary alliance. Therefore, we should fully consider the above risk factors and continuously accumulate valuable experience in constructing and operating the cross-boundary alliance symbiosis system from theoretical and practical perspectives.

### *2.2. Principal–Agent Relationship of Knowledge-Sharing in Cross-Boundary Alliance Symbiosis Systems*

The cross-boundary alliance symbiosis system is an organizational system for sharing and transferring cross-domain knowledge resources. Symbiosis units in the system cooperate to improve their adaptability to the environment and realize knowledge resource-sharing based on synergistic symbiosis. From the perspective of economics, the knowledge-sharing behavior among members of a cross-boundary alliance is a cooperative activity with mutual dependence and benefit-sharing.

In the innovation demand of new products and services, the cooperative relationship among alliance members is formed through knowledge resource transactions with a contract as the link. As shown in Figure 2, the knowledge-sharing process among the symbiotic units in the cross-boundary alliance symbiosis system is mainly completed by the knowledge provider, the knowledge receiver, the knowledge resource, and the knowledge-sharing context. Under the joint influence of internal and external environmental factors such as knowledge-sharing willingness, knowledge dissemination ability, product innovation opportunities, and market demand, each symbiotic unit takes the pursuit of benefit maximization as the goal, forms the principal–agent relationship of knowledge resource-sharing under the condition of information asymmetry, and carries on the continuous game. Based on the principal–agent relationship, symbiosis units carry out continuous symbiotic game activities, realize the optimal allocation of knowledge resources of the alliance under the symbiotic vision of benefit-sharing and risk sharing, and complete collaborative innovation among alliance members.

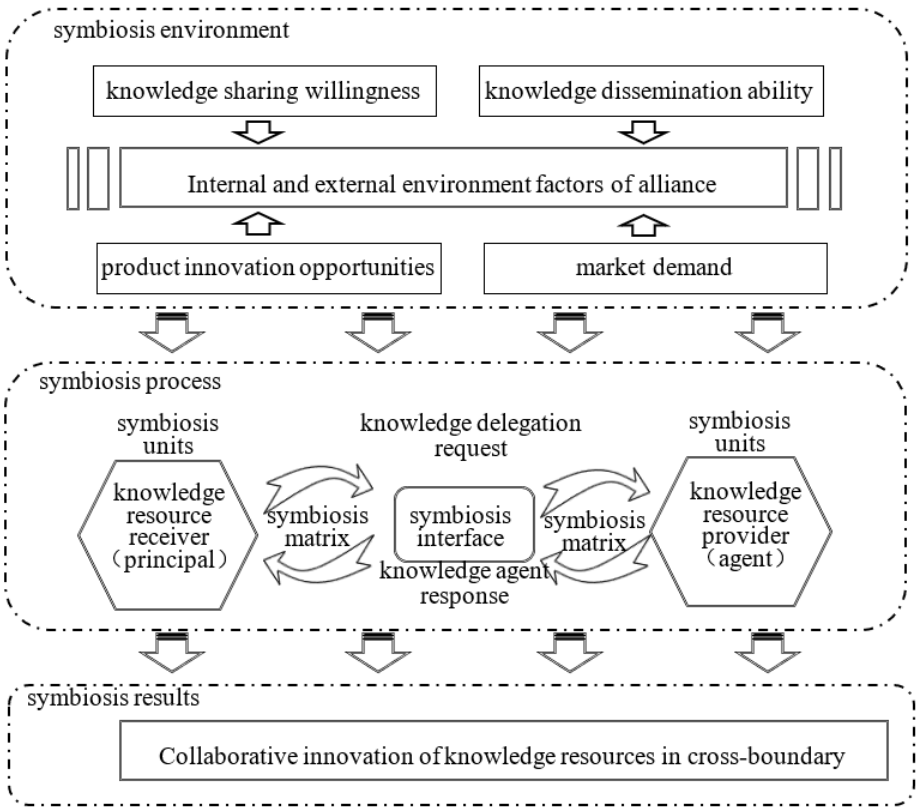


**Figure 2.** Activity diagram of knowledge-sharing principal agent in a symbiotic system.

The principal–agent relationship mainly refers to an economic relationship between the subjects of the market economy under the condition of information asymmetry [41,42]. In the process of cross-boundary knowledge-sharing, alliance members seek knowledge help or delegate them to provide knowledge resources according to their knowledge gap and at the same time, pay them remuneration [43]. Thus, the principal–agent relationship based on knowledge resources is formed between alliance members. Under the conditions of information asymmetry, the knowledge resource-sharing partners with the principal–agent relationship are pursuing the maximization of their respective benefits to ensure that the income of both partners is asymmetrical. Additionally, the knowledge agent can easily produce opportunistic behaviors, which will damage the interests of the principal. Especially in the process of cross-boundary cooperation, the ecological niche difference between the principal and the agent is large, and the sharing of cross-boundary knowledge will be hindered by multi-dimensional boundaries such as industry, geography, and cognition. At the same time, the knowledge principal has certain information disadvantages in terms of the knowledge level, effort, and sharing intention of the knowledge agent. In order to guarantee the effectiveness of knowledge resource acquisition, the principal will increase the payment coefficient to encourage the agent's willingness to share so that the two sides can reach the equilibrium of the game as soon as possible. Therefore, in the transboundary alliance symbiosis system, the knowledge-sharing process of each symbiosis unit conforms to the principal–agent relationship. In this case, it is necessary to design a reasonable incentive contract to encourage the alliance members to choose favorable actions under certain conditions so that both the principal and agent can share the output value of the alliance and bear the random risk of the alliance. This kind of knowledge resource principal–agent symbiosis mode is the key to maintain the stable operation of the alliance symbiosis system and realize the maximization of both the overall benefits and balance of interests.

## 3. The Model

The principal–agent theory is often used in the design of incentive mechanisms [44,45]. Long et al. analyzed the equilibriums of the principal–agent in different knowledge inputs [46]. According to the principal–agent theory, Liu et al. studied the relationship between the social benefits coefficient and both the patent benefits coefficient and incentive coefficient [47], while Wang et al. established the basic incentive model and optimization model of knowledge-sharing in the industrial building supply chain [48]. Based on the research results of these scholars, combined with the characteristics of the knowledge-sharing activities of the cross-boundary, this paper comprehensively considers the differences in the knowledge level, knowledge field, and symbiotic environment between the principal and agent, and constructs the optimal incentive mechanism of knowledge-sharing strategies in cross-boundary alliances. This research solves the optimal incentive coefficient, the optimal effort level, and the corresponding profits of the symbiotic partners in the knowledge-sharing activities of the cross-boundary alliance, thus providing the basis for the construction of cross-boundary alliance knowledge-sharing models.

### *3.1. Model Hypothesis*

**Hypothesis 1 (H1).** *The two symbiosis units of knowledge-sharing in the symbiosis system of cross-boundary innovation alliances are both the pursuers of rational benefit maximization. They belong to different niche spaces and are affected by the symbiotic environment, and their proprietary knowledge is quite different. The principal is a demand for knowledge, denoted as R. The agent is the overflow of knowledge, denoted as S.*

**Hypothesis 2 (H2).** *a is the knowledge-sharing effort level of the knowledge agent in the symbiotic unit, wherein* $a \geq 1$*. The higher the coefficient, the more effort the agent makes in knowledge-sharing. When* $a = 1$*, it indicates that the agent did not make any effort.*

**Hypothesis 3 (H3).** *The difference in knowledge is the leading cause of knowledge-sharing and spreading [49,50]. The effect of knowledge-sharing depends on the ability of knowledge dissemination [51]. When knowledge in different fields is shared and transferred, the knowledge potential difference is in an 'inverted U' shape with the knowledge transmission ability in knowledge-sharing. When the knowledge potential difference is located at the vertex of the 'inverted U' shape, the knowledge transmission ability is the highest. When the knowledge potential difference is smaller than the vertex value, the following is true: the higher the knowledge similarity and the smaller the knowledge potential difference between the symbiosis units, the more disadvantageous it is to the knowledge dissemination and fusion. When the knowledge potential difference is too large, the ability of knowledge transmission will decrease with the increase of the knowledge potential difference due to the barriers of knowledge understanding and absorption among the symbiotic units. Therefore, this research study set the coefficient of knowledge transmission ability in the process of knowledge-sharing as follows:*

$$y = mx^2 + nx \tag{1}$$

*where x is the cross-boundary knowledge potential difference of two symbiotic units; m and n are each constant; and* $m < 0$, $0 \leq y \leq 1$.

**Hypothesis 4 (H4).** *H is the uncertain factors affecting knowledge-sharing outside the alliance in the symbiotic environment. It obeys the normal distribution with a mean of 0 and variance of* $\delta_H^2$, $H \sim N(0, \delta_H^2)$. *Therefore, refer to the views of scholars such as Holmstrom and Milgrom concerning that linear relationships can lead to optimal returns. Set K as the total amount of the knowledge level and then the shared knowledge output function of knowledge agents can be expressed as follows:*

$$\pi = Kay + H \tag{2}$$

**Hypothesis 5 (H5).** *The knowledge-sharing environment among symbiotic units in the cross-boundary alliance is relatively complex [52], which is usually affected by many aspects, such as the organizational relationship, technological difference, and geographical distance within the alliance. I is the internal environment factor of alliance in the symbiotic environment. I is related to the external environment H but it has nothing to do with the effort level a of the knowledge agent. Additionally, it obeys the normal distribution with a mean of 0 and variance of* $\delta_I^2$, $I \sim N(0, \delta_I^2)$.

**Hypothesis 6 (H6).** *Through the acquisition and integration of cross-domain knowledge resources, the knowledge principal can increase the knowledge increment, innovate cross-boundary products or services, and gain profits.* $\eta$ *is the degree of the principal's effort in the integration and innovation after learning new knowledge. Referring to the Cobb–Douglas production function, the basic production function of new knowledge can be expressed as* $\Delta\pi = \eta^{\varepsilon}\pi^{\varphi}$, *where* $\varepsilon$ *is the contribution level of the research input to the knowledge production and* $\varphi$ *is the contribution level of the knowledge quantity to the knowledge production. When* $\varepsilon = 1$, $\varphi = 1$, *the production of new knowledge is proportional to the level of research effort and they are linearly dependent. Meanwhile, knowledge-sharing has a significant positive effect on the principal's income. In addition, the knowledge-sharing activities of cross-boundary alliances are affected and acted by the internal environment within the alliance.* $\gamma$ *is the influence coefficient of internal environment I on the profit of the knowledge principal. Therefore, the principal's income can be expressed as follows:*

$$w_r = \eta\pi + \gamma I \tag{3}$$

**Hypothesis 7 (H7).** *In order to encourage symbiotic partners to actively participate in knowledge-sharing activities within the alliance, the knowledge principal will pay an incentive remuneration to the knowledge agent according to its income.* $\beta$ *is the incentive coefficient and* $0 \leq \beta \leq 1$. *Suppose* $\alpha$ *is the fixed income of the knowledge agent; then, the income of the knowledge agent is:*

$$w_s = \alpha + \beta(\eta\pi + \gamma I - \alpha) \tag{4}$$

**Hypothesis 8 (H8).** *Symbiotic partners in the cross-boundary alliance have a certain sharing costs in the principal–agent process of knowledge-sharing. According to the theory of information economics [27], sharing cost is a function of the effort level. $b_r$ and $b_s$ are the coefficient of the sharing cost; then, the sharing costs of the principal and agent are as follows:*

$$c_r = \frac{1}{2} b_r \eta^2 \tag{5}$$

$$c_s = \frac{1}{2} b_s a^2 \tag{6}$$

**Hypothesis 9 (H9).** *In the symbiotic system of the cross-boundary alliance, because of the trans-boundary nature of the knowledge domain, the dynamic nature of the innovation demand, and the complexity of the symbiotic environment, there are many risks brought by uncertain factors to all the knowledge-sharing activities. It is assumed that the utility function of symbiotic partners in the alliance has the property of invariant absolute risk avoidance. According to the research conclusion of Hsu [53], the risk utility function of the principal and agent is as follows:*

$$u_r(\lambda_r) = -e^{-\rho_r \lambda_r} \tag{7}$$

$$u_s(\lambda_s) = -e^{-\rho_s \lambda_s} \tag{8}$$

*where $\lambda_r$ and $\lambda_s$ are the actual income of the principal–agent symbiotic units participating in knowledge-sharing and both $\rho_r$ and $\rho_s$ are the risk aversion coefficients of the knowledge-sharing of the symbiotic unit of the alliance. The larger $\rho$, the more risk-averse the symbiotic units.*

### *3.2. Model Construction*

#### 3.2.1. Expected Income of Knowledge Principal

The actual income $\lambda_r$ of the knowledge principal is the income of the knowledge principal minus the incentive reward and sharing cost. It can be expressed as follows:

$$\lambda_r = w_r - w_s - c_r = (1-\beta)[\eta(Kay + H) + \gamma I - \alpha] - \frac{1}{2} b_r \eta^2 \tag{9}$$

The expected income of the knowledge principal is

$$E(\lambda_r) = (1-\beta)(\eta Kay - \alpha) - \frac{1}{2} b_r \eta^2 \tag{10}$$

and the variance of the knowledge principal's income is

$$D(\lambda_r) = (1-\beta)^2 \left(\eta^2 \delta_H^2 + \gamma^2 \delta_I^2 + 2\eta\gamma \mathrm{cov}(\pi, I)\right) \tag{11}$$

The actual income $\lambda_r$ obeys the normal distribution with the mean of $E(\lambda_r)$ and variance of $D(\lambda_r)$,$\lambda_r \sim N\left((1-\beta)(\eta Kay - \alpha) - \frac{1}{2} b_r \eta^2, (1-\beta)^2 \left(\eta^2 \delta_H^2 + \gamma^2 \delta_I^2 + 2\eta\gamma \mathrm{cov}(\pi, I)\right)\right)$.

According to the hypothesis, the principal of knowledge-sharing adopts a risk-averse strategy and the degree of risk-aversiveness can be defined by the Arrow–Pratt method: $\rho_r = -\frac{u(\lambda_r)''}{u(\lambda_r)'} > 0$. The risk cost of the knowledge-sharing principal can be expressed as follows:

$$F_r = \frac{1}{2} \rho_r D(\lambda_r) \tag{12}$$

According to the principle of economics, the utility level corresponding to the certainty equivalent income is equivalent to the utility level of the expected income under the condition of uncertainty. The certainty equivalent income of the knowledge principal is the expected mean minus the risk cost under the uncertain condition. In this case, the maximization of the expected income of the knowledge principal is equivalent to the

maximization of the deterministic equivalent income. That is, the deterministic equivalent income of the knowledge principal is as follows:

$$CE_r = E(\lambda_r) - F_r = E(\lambda_r) - \frac{1}{2}\rho_r D(\lambda_r) \tag{13}$$

3.2.2. Expected Income of Knowledge Agent

The actual income $\lambda_s$ of the knowledge agent is the income of the knowledge-sharing minus the knowledge-sharing cost. It can be expressed as follows:

$$\lambda_s = w_s - c_s = \alpha(1-\beta) + \beta\eta(Kay + H) + \beta\gamma I - \frac{1}{2}b_s a^2 \tag{14}$$

The expected income of the knowledge agent is

$$E(\lambda_s) = \alpha(1-\beta) + \beta\eta Kay - \frac{1}{2}b_s a^2 \tag{15}$$

and the variance of the knowledge agent's income is

$$D(\lambda_s) = \beta^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \tag{16}$$

The actual income $\lambda_s$ obeys the normal distribution with the mean of $E(\lambda_s)$ and variance of $D(\lambda_s)$, $\lambda_s \sim N\left(\alpha(1-\beta) + \beta\eta Kay - \frac{1}{2}b_s a^2, \beta^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)\right)$. The risk cost of the knowledge-sharing agent can be expressed as follows:

$$F_s = \frac{1}{2}\rho_s D(\lambda_s) \tag{17}$$

According to the utility function characteristics of the knowledge agent, its deterministic equivalent income is:

$$CE_s = E(\lambda_s) - F_s = E(\lambda_s) - \frac{1}{2}\rho_s D(\lambda_s) \tag{18}$$

This indicates that the utility level corresponding to the deterministic equivalent income of the knowledge agent is equivalent to the utility level of the expected income under the uncertain condition. In addition, the maximization of the expected income of knowledge-sharing by the knowledge agent is equivalent to the maximization of the pursuit of the deterministic equivalent income.

3.2.3. Knowledge-Sharing Incentive Model

By adjusting the incentive coefficient $\beta$, the symbiosis unit in the symbiosis system can encourage the knowledge agent to increase the effort degree $\alpha$ of knowledge-sharing to maximize the benefits of knowledge-sharing for the symbiotic partners in the alliance. According to the theory of incentive compatibility, on the basis of satisfying the constraint and incentive of knowledge-sharing for the knowledge agent, the expected income of the knowledge principal can be maximized. It is assumed that the premise of the knowledge agent responding to the knowledge-sharing request is to obtain the minimum revenue of $w_0$. In other words, the constraint of knowledge-sharing activity is $CE_s \geq w_0$. Therefore, the principal–agent model of knowledge-sharing can be expressed as follows

$$s.t.\begin{cases} \max CE_r = E(\lambda_r) - F_r \\ (IC)\max CE_s = E(\lambda_s) - F_s \\ (IR)E(\lambda_s) - F_s \geq w_0 \end{cases} \tag{19}$$

because the principal and agent of the symbiotic unit of the cross-boundary alliance are risk-averse, that is $\rho_r > 0$, $\rho_s > 0$.

Firstly, incentive compatible constraint *IC* calculates the first and second order differential of knowledge-sharing willingness $a$. The results of the differential are $\frac{\partial CE_s}{\partial a} = \beta\eta Ky - b_s a$, $\frac{\partial^2 CE_s}{\partial a^2} = -b_s < 0$. Thus, when $\frac{\partial CE_s}{\partial a} = \beta\eta Ky - b_s a = 0$, $CE_s$ can derive the maximum value. In this case, knowledge-sharing willingness $a$ can be solved as follows:

$$a = \frac{\beta\eta yK}{b_s} \tag{20}$$

Under the Kuhn–Tucker condition, if the Lagrange multiplier of inequality *IR* in the model is not 0, the equal sign of inequality *IR* holds. Under the optimal conditions, when the knowledge agent is willing to share knowledge, the principal may not pay more. The principal–agent model of knowledge-sharing can be changed as follows:

$$\begin{gathered} \max CE_r = E(\lambda_r) - F_r \\ s.t. \begin{cases} (IC) a = \frac{\beta\eta yK}{b_s} \\ (IR) E(\lambda_s) - F_s = w_0 \end{cases} \end{gathered} \tag{21}$$

Taking the *IC* and *IR* constraints of the upper formula into the objective function $\max CE_r$, we can derive that:

$$\max CE_r = \frac{\eta^2 K^2 y^2 \beta}{b_s} - \frac{\eta^2 K^2 y^2 \beta^2}{2b_s} - \frac{b_r \eta^2}{2} - \frac{1}{2}\left[\rho_s \beta^2 + \rho_r (1-\beta)^2\right]\left(\eta^2 \delta_H^2 + \gamma^2 \delta_I^2 + 2\eta\gamma \mathrm{cov}(\pi, I)\right) - w_0 \tag{22}$$

Take the first and second derivatives of the above formula with respect to $\beta$ and $\gamma$; then, we can derive that $\frac{\partial^2 CE_r}{\partial \beta^2} \leq 0$, $\frac{\partial^2 CE_r}{\partial \gamma^2} \leq 0$. When $\frac{\partial CE_r}{\partial \beta} = 0, \frac{\partial CE_r}{\partial \gamma} = 0$, the principal's equivalent income function is maximized and both $\gamma$ and $\beta$ can be solved:

$$\gamma^* = -\frac{\eta \mathrm{cov}(\pi, I)}{\delta_I^2} \tag{23}$$

$$\beta^* = \frac{K^2 y^2 \delta_I^2 + \rho_r b_s \left(\delta_H^2 \delta_I^2 - \mathrm{cov}^2(\pi, I)\right)}{K^2 y^2 \delta_I^2 + b_s (\rho_s + \rho_r)\left(\delta_H^2 \delta_I^2 - \mathrm{cov}^2(\pi, I)\right)} \tag{24}$$

Take the above results into Formula (20); $a$ can be solved:

$$a^* = \frac{\beta\eta Ky}{b_s} = \frac{\eta Ky\left(K^2 y^2 \delta_I^2 + \rho_r b_s \left(\delta_H^2 \delta_I^2 - \mathrm{cov}^2(\pi, I)\right)\right)}{b_s K^2 y^2 \delta_I^2 + b_s^2 (\rho_s + \rho_r)\left(\delta_H^2 \delta_I^2 - \mathrm{cov}^2(\pi, I)\right)} \tag{25}$$

In this case, $a^*$ and $\beta^*$ are substituted into the objective function $CE_r$ to maximize the equivalent income of the knowledge principal. The detailed solution process of this model is shown in Appendix A.

## 4. Results and Discussion

### *4.1. Model Output*

This paper adds the alliance symbiotic environment influence variable, knowledge transmission ability variable, cross-boundary knowledge potential difference variable, and the principal's knowledge absorption and innovation effort variable into the principal–agent model. This paper analyzes the intensity of the incentive coefficient $\beta$, the effort level $a$ of the knowledge-sharing agent, as well as factors such as the sharing environmental impact factor, and has obtained the following analysis results.

1. Correlation analysis between the internal environment and the external environment of symbiotic systems

According to the analysis of Equations (24) and (25), because of the correlation between the internal and external factors of the alliance in the symbiotic environment, it can be concluded that: $\delta_H^2 \delta_I^2 - \mathrm{cov}^2(\pi, I) \geq 0$.

When $\delta_H^2\delta_I^2 - \mathrm{cov}^2(\pi, I) = 0$, it is fully related to both. At the point $\beta = 1$, the agent does not assume any risk.

When $\delta_H^2\delta_I^2 - \mathrm{cov}^2(\pi, I) > 0$, it can be concluded that $\frac{\partial\beta^*}{\partial b_s} < 0$, $\frac{\partial a^*}{\partial b_s} < 0$, $\frac{\partial\beta^*}{\partial\rho_s} < 0$, $\frac{\partial a^*}{\partial\rho_s} < 0$, $\frac{\partial\beta^*}{\partial\delta_H} < 0$, $\frac{\partial a^*}{\partial\delta_H} < 0$, $\frac{\partial\beta^*}{\partial\delta_I} < 0$, $\frac{\partial a^*}{\partial\delta_I} < 0$, $\frac{\partial\beta^*}{\partial\rho_r} > 0$, $\frac{\partial a^*}{\partial\rho_r} > 0$, $\frac{\partial\beta^*}{\partial y} > 0$, $\frac{\partial a^*}{\partial y} > 0$. The above results show that the incentive coefficient of knowledge-sharing is negatively correlated with the cost coefficient of the agent, the degree of risk aversion, and the output variance of the symbiotic environment, and positively correlated with the degree of risk aversion and the ability of knowledge dissemination of the principal. This shows that when the cost coefficient is fixed, the more reluctant the knowledge agents are to share knowledge; the more they want to avoid risks; and the optimal incentive coefficient is also lower at this time.

2. Influence analysis of the knowledge potential difference on the knowledge sharing activities

For the coefficient of knowledge transmission ability $y = mx^2 + nx$, this paper analyzes the influence of knowledge potential difference on knowledge-sharing activities among symbiotic units of the cross-boundary alliance from the following three situations.

Firstly, when the knowledge potential difference approaches 0, the degree of knowledge difference between symbiotic units is little or almost no difference. Then:

$$\lim_{x\to 0}\beta^* = \lim_{x\to 0}\frac{\eta^2K^2\left(mx^2+nx\right)^2 + \rho_r b_s\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)}{\eta^2K^2(mx^2+nx)^2 + b_s(\rho_s+\rho_r)\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)} = \frac{\rho_r}{\rho_s+\rho_r}$$

$$\lim_{x\to 0}a^* = \lim_{x\to 0}\frac{\eta K\left(mx^2+nx\right)\left[\eta^2K^2\left(mx^2+nx\right)^2 + \rho_r b_s\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)\right]}{b_s\eta^2K^2(mx^2+nx)^2 + b_s^2(\rho_s+\rho_r)\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)} = 0$$

At this time, the knowledge homogenization between the principal and agent in the symbiotic units is serious. The principal has no urgent need for the knowledge of the agent. The alliance cross-boundary innovation activities, based on the knowledge cooperation, are challenging to carry out. The alliance innovation development space is limited and the knowledge agent has no willingness to share. Thus, the principal–agent relationship of knowledge-sharing will not be established.

Secondly, when the knowledge potential difference is very large and approaches infinity, there is a huge difference in the amount of knowledge in a particular field between the knowledge principal and the knowledge agent. Then:

$$\lim_{x\to\infty}\beta^* = \lim_{x\to\infty}\frac{\eta^2K^2\left(mx^2+nx\right)^2+\rho_r b_s\left(\eta^2\delta_H^2+\gamma^2\delta_I^2+2\eta\gamma\mathrm{cov}(\pi,I)\right)}{\eta^2K^2(mx^2+nx)^2+b_s(\rho_s+\rho_r)\left(\eta^2\delta_H^2+\gamma^2\delta_I^2+2\eta\gamma\mathrm{cov}(\pi,I)\right)} = 1$$

$$\lim_{x\to\infty}a^* = \lim_{x\to\infty}\frac{\eta K\left(mx^2+nx\right)\left[\eta^2K^2\left(mx^2+nx\right)^2+\rho_r b_s\left(\eta^2\delta_H^2+\gamma^2\delta_I^2+2\eta\gamma\mathrm{cov}(\pi,I)\right)\right]}{b_s\eta^2K^2(mx^2+nx)^2+b_s^2(\rho_s+\rho_r)\left(\eta^2\delta_H^2+\gamma^2\delta_I^2+2\eta\gamma\mathrm{cov}(\pi,I)\right)} = \infty$$

Suppose the knowledge agent is willing to participate in the knowledge-sharing activities. In that case, it is bound to make unlimited efforts to overcome the technical boundaries and make up for the sharing obstacles caused by the large knowledge potential difference. Due to the large gap in the domain knowledge between the knowledge principal and its symbiotic partners, the knowledge principal also needs to make infinite efforts to learn, absorb, and transform new knowledge. At this point, both the principal and the agent need to spend a high cost of sharing. Additionally, the cooperation between them is difficult, which makes the cross-boundary cooperation based on knowledge-sharing impossible.

Thirdly, according to the hypothesis of the knowledge transfer capability coefficient $y = mx^2 + nx(0 \le y \le 1,\ m < 0)$, it can be known that when $n \ge 2\sqrt{-m}$, there is $\frac{-n+\sqrt{n^2+4m}}{2m} \le x \le \frac{-n-\sqrt{n^2+4m}}{2m}$. When the knowledge potential difference is $x' = -\frac{n}{2m}$, the

coefficient of knowledge transferability reaches the maximum. The amount of knowledge-sharing affected by the knowledge potential difference reaches the top. In this case, $a$ and $\beta$ will be affected by other factors besides knowledge potential difference. Then:

$$\lim_{x \to x'} \beta^* = \frac{16 b_s m^2 \rho_r \left(\eta^2 \delta_H^2 + \gamma^2 \delta_I^2 + 2\eta\gamma \mathrm{cov}(\pi, I)\right) + \eta^2 K^2 n^4}{16 b_s m^2 (\rho_s + \rho_r) \left(\eta^2 \delta_H^2 + \gamma^2 \delta_I^2 + 2\eta\gamma \mathrm{cov}(\pi, I)\right) + \eta^2 K^2 n^4}$$

$$\lim_{x \to x'} \alpha^* = -\frac{K\eta n^2 \left(K^2 \eta^2 n^4 + 16 m^2 \rho_r b_s \left(\eta^2 \delta_H^2 + \gamma^2 \delta_I^2 + 2\eta\gamma \mathrm{cov}(\pi, I)\right)\right)}{4 b_s m \left(K^2 \eta^2 n^4 + 16 m^2 b_s (\rho_s + \rho_r) \left(\eta^2 \delta_H^2 + \gamma^2 \delta_I^2 + 2\eta\gamma \mathrm{cov}(\pi, I)\right)\right)}$$

When $\frac{-n+\sqrt{n^2+4m}}{2m} < x < \frac{-n}{2m}$, there is $\frac{\partial \beta^*}{\partial x} > 0$, $\frac{\partial a^*}{\partial x} > 0$. This means that when the knowledge potential difference is within this range, the incentive coefficient and the effort level of the knowledge agent are constantly increasing with the increase of the knowledge distance. When $\frac{-n}{2m} < x < \frac{-n-\sqrt{n^2+4m}}{2m}$, there is $\frac{\partial \beta^*}{\partial x} < 0$, $\frac{\partial a^*}{\partial x} < 0$. This means that when the knowledge potential difference is within this range, with the rise of knowledge distance, the incentive coefficient and the effort level of the knowledge agent decrease continuously. This indicates that too large or too small knowledge potential difference is not conducive to knowledge-sharing among symbiotic partners within the alliance and a certain degree of knowledge distance is conducive to knowledge fusion and symbiosis among members of the cross-boundary alliance.

3. Influence analysis of the symbiotic environment on the knowledge-sharing activities

As for the influence of the symbiotic environment on knowledge-sharing, this paper analyzes it from the following two aspects.

Firstly, when $\mathrm{cov}(\pi, I) > 0$, $\pi$ is positively correlated with $I$. If $I > 0$, this means that the symbiotic environment of the alliance provides a positive cooperative condition for the transfer and acquisition of knowledge among symbiotic units. This indicates that in the principal–agent process of knowledge-sharing, the symbiotic environment has a strong positive influence ability. The increase of knowledge output is related to the market and opportunity outside the alliance but has little to do with the agent's effort level. Therefore, under the constraint and management of the alliance knowledge-sharing environment, the reward incentive of the agent can be reduced appropriately to save the cost of principal–agent. If $I < 0$, this means that the external influence factors of the alliance in the symbiotic environment also fail to play a positive role in knowledge-sharing. In this case, if the alliance wants to complete knowledge-sharing and transfer, the knowledge agent needs to pay a higher level of effort. Therefore, the remuneration to the agent can be increased to ensure continuous knowledge-sharing activities.

When $\mathrm{cov}(\pi, I) < 0$, $\pi$ is negatively correlated with $I$. If $I > 0$, this shows that although the alliance environment can promote knowledge-sharing, the uncertain factors of the external environment provide relatively negative external conditions for knowledge-sharing among symbiotic units. The output of knowledge-sharing mainly depends on the effort level of the knowledge agent. Therefore, it is necessary to increase the agent's remuneration and encourage the knowledge agent's willingness to share. If $I < 0$, this means that the output of knowledge-sharing in the symbiotic system is positively affected by the external environment of the alliance and appropriately reducing the agent's remuneration will not affect the production of knowledge-sharing.

Secondly, this paper compares the incentive of knowledge-sharing under general conditions without environmental impact factors of cross-boundary alliances with the incentive of knowledge-sharing in the cross-boundary alliances. According to the hypothesis condition, in the case of no environmental influencing factors of the cross-boundary alliance, the incentive coefficient of knowledge-sharing is obtained as follows:

$$\beta^{**} = \frac{K^2 y^2 + \rho_r b_s \delta_H^2}{K^2 y^2 + (\rho_s + \rho_r) b_s \delta_H^2} \tag{26}$$

By comparing Formulas (24) and (26), there is $\beta^* > \beta^{**}$. This shows that the knowledge agent can acquire higher incentive rewards and reduce the risk of the principal with the participation of the cross-boundary alliance environment.

### *4.2. Model Simulation*

In this paper, a numerical simulation is carried out on the basis of comprehensively considering the influence factors such as knowledge transferability, knowledge absorptive ability, the uncertainty of the knowledge-sharing process, and the alliance environment. The simulation results can supplement and support the results of the above model analysis. The primary parameter settings are shown in Table 1.

**Table 1.** Parameter initial value.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $K$ | 10 | $\eta$ | 2 |
| $y$ | 0.8 | $w_0$ | 4 |
| $\delta_H$ | 5 | $\delta_I$ | 5 |
| $b_s$ | 0.6 | $b_r$ | 0.6 |
| $\rho_s$ | 2 | $\rho_r$ | 1 |
| $\alpha$ | 4 | $\mathrm{cov}(\pi, I)$ | 0.5 |
| $n$ | 6 | $m$ | −5 |

#### 4.2.1. Influence of the Incentive Coefficient of Knowledge-Sharing and Effort Level of the Knowledge-Sharing Unit on the Principal's Profit

In the case of a certain knowledge potential difference, the above fundamental variable values are substituted into the principal's equivalent income max$CE_r$. The simulation data is obtained by using the simulation software Maple 2020, as shown in Figure 3. Based on the analysis of the principal's income surface, it can be seen that the effort level of the knowledge-sharing agent and the sharing incentive coefficient have an 'inverted U' relationship with the principal's income. Too little or too much effort and the incentive coefficient of knowledge-sharing cannot improve the overall profit of both the principal and agent. When $a < a^*$,$\beta < \beta^*$, with the increase of the incentive coefficient and the agent's efforts, both the intellectual output and the principal's income gradually increase. When $a > a^*$, $\beta > \beta^*$, with the further increase of the incentive coefficient and shared efforts, the fee paid by the principal to the agent will gradually exceed the income brought by the increase of the knowledge-sharing effort. This makes its overall income level decline. At the same time, as shown in Figure 4, the relationship between the incentive coefficient, the agent's knowledge-sharing effort, and both the principal's integration innovation effort and income are also regulated by $\delta_H$ and $\delta_I$. The smaller the variance, the more stable the symbiosis environment and the faster the collaborative innovation of the alliance; additionally, the symbiosis unit will acquire better benefits.

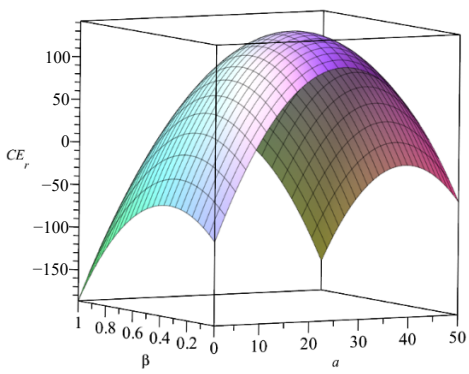


**Figure 3.** Three-dimensional relationship diagram of the influence of the incentive coefficient and sharing intention on the principal's income.

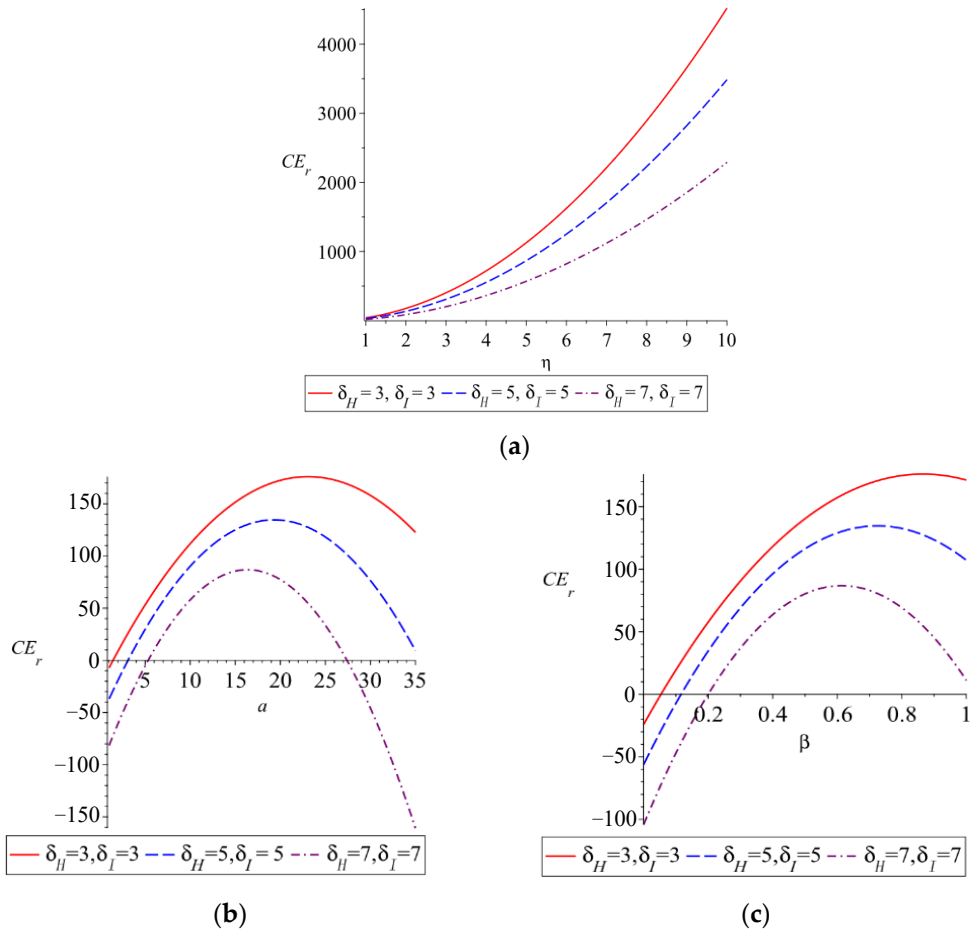


**Figure 4.** The relationship of the effect of model influencing factors on the principal's income in different symbiosis environments; (**a**) relationship diagram between the principal's integrated innovation efforts and its revenue in different symbiosis environments; (**b**) relationship diagram between the agent's knowledge-sharing efforts and the principal's revenue in different symbiosis environments; and (**c**) relationship diagram between the incentive coefficient and the principal's revenue in different symbiosis environments.

#### 4.2.2. Influence of the Risk Aversion Coefficient of Knowledge-Sharing on the Incentive Coefficient

To share heterogeneous knowledge, cross-boundary organizations form mutually beneficial strategic alliances. Due to the cross-boundary nature of the industries, regions, and knowledge reserves of the alliance members, symbiotic partners in the early stage of cooperation usually cannot accurately judge the extent of their efforts and contributions. Therefore, in knowledge-sharing activities, both the principal and agent often adopt the risk-averse strategy. As shown in Figure 5, the study found that the more the agent avoided risk, the lower the optimal incentive coefficient and the stronger the tendency of the incentive coefficient to decrease; the more risk-averse the principal, the higher the incentive coefficient and the slower the changing trend of the incentive coefficient.

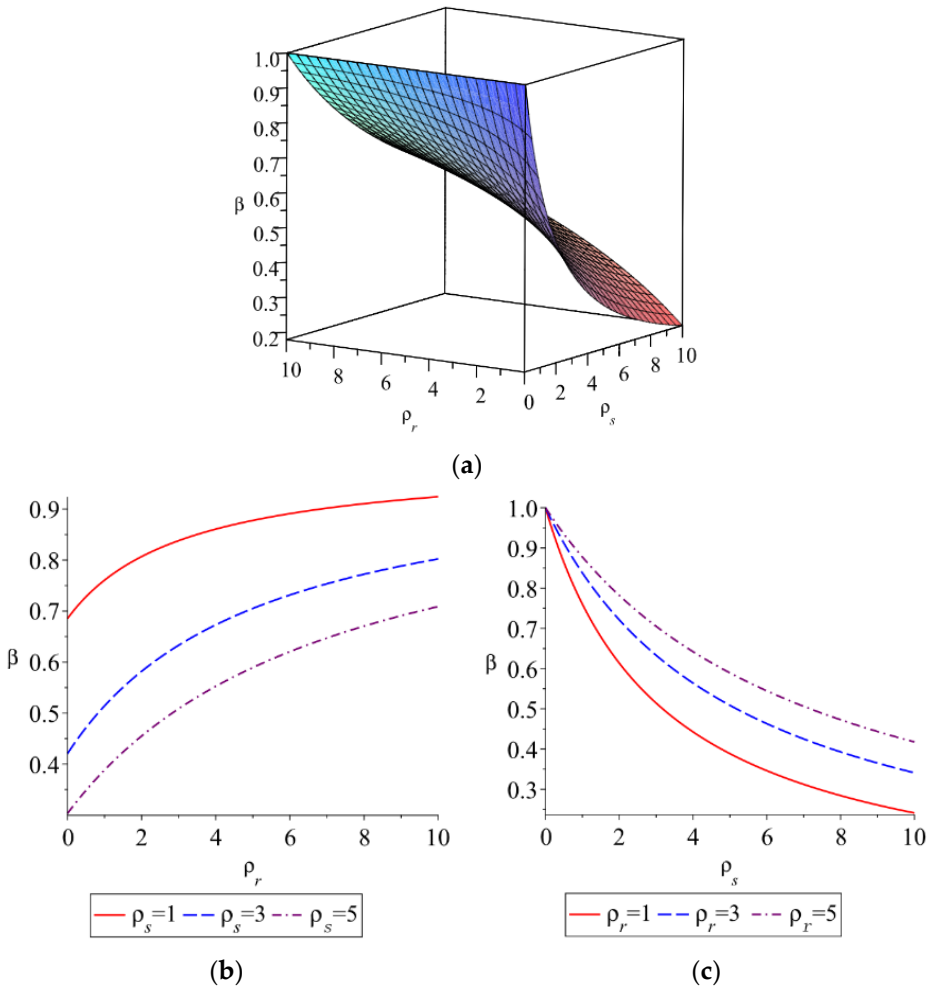


**Figure 5.** Relationship of the influence of the risk aversion degree of symbiotic partners on the incentive coefficient: (**a**) three-dimensional relationship diagram of the influence of the risk aversion degree of symbiotic partners on the incentive coefficient; (**b**) relationship between the principal's risk aversion coefficient and the optimal incentive coefficient; and (**c**) relationship between the agent's risk aversion coefficient and the optimal incentive coefficient.

#### 4.2.3. Influence of the Knowledge Potential Difference on the Incentive Coefficient and Agent's Effort

In the symbiotic system of the cross-boundary alliance, there are significant differences in the knowledge structure among members. Such differences and the knowledge demand of the principal make the cross-boundary knowledge of the alliance evolve and increase with the continuous flow of information and resources. As shown in Figure 6, it is found that the knowledge potential difference has an 'inverted U' relationship with the incentive coefficient and the effort of the knowledge-sharing agent within its value range. When $x = -\frac{n}{2m}$, the incentive coefficient of knowledge-sharing is maximum and the agent's effort degree is maximum.

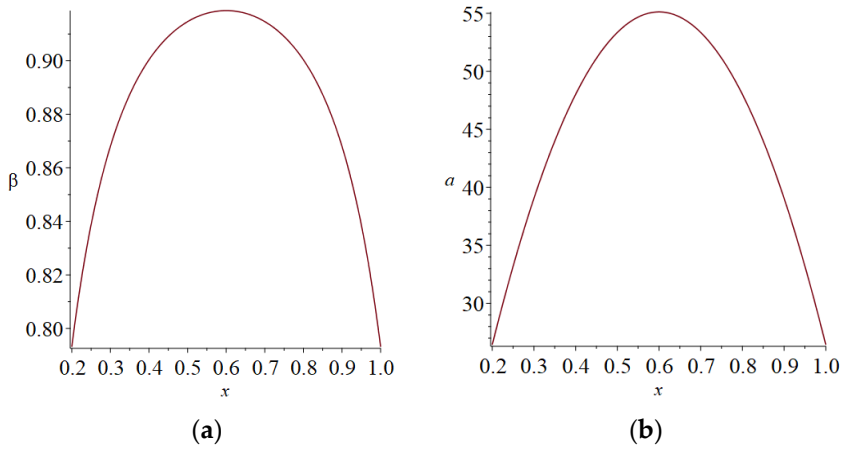


**Figure 6.** Influence of the knowledge potential difference of symbiotic partners on the incentive coefficient and sharing effort of agents: (**a**) relationship between the knowledge potential difference and optimal incentive coefficient among members, and (**b**) relationship between the knowledge potential difference among members and the degree of knowledge-sharing efforts of the agent.

## 5. Conclusions

The cross-boundary alliance provides a mutually beneficial and symbiotic organizational environment for members to carry out cross-border cooperation. In order to achieve the collaborative goal of cross-boundary innovation and value co-creation, there is a great amount of cross-domain knowledge-sharing, absorption, utilization, and innovation activities among alliance members. In this process, the knowledge-sharing activities among the members of the alliance show remarkable symbiosis characteristics. Under the influence of the internal and external environment of the alliance, cross-border knowledge-sharing is used as a link to establish mutually beneficial symbiotic cooperation. This paper constructs the cross-boundary alliance symbiosis system and further constructs the principal–agent model of knowledge-sharing in the symbiosis system. The research results show that the complexity and dynamics of the knowledge-sharing process determine that the sharing incentives are affected by many factors. Accurate identification of the factors that affect the incentive of knowledge-sharing can enhance the stability and sustainability of knowledge-sharing activities within the system. The conclusions of this paper are as follows.

(1) Symbiosis is an effective mode of cross-boundary alliance operation. Knowledge resource-sharing based on the symbiotic system of the cross-boundary alliance is the basis of the collaborative innovation of alliance members. The alliance members create and transfer values on the cross-boundary level and produce a symbiotic relationship of mutual dependence, which improves the efficiency of the use of alliance knowledge resources. This paper analyzes the symbiosis and interrelationship of cross-boundary alliance knowledge-sharing. It explores the principal–agent relationship between symbiotic units in the symbiotic system in the alliance collaborative innovation activities. The research shows that the symbiotic environment of the cross-boundary alliance has a significant impact on knowledge-sharing activities. Cultivating a positive, healthy, and orderly mutualistic environment can restrain the negative behavior of symbiotic units and shape good behavioral norms. This helps to accelerate information transmission and knowledge flow, reduce the cost of knowledge-sharing, and improve the ability to acquire, absorb, and utilize knowledge resources.

(2) The knowledge-sharing activities of the cross-boundary alliance members are affected by the alliance knowledge potential difference, the agent's willingness to share knowledge, and the principal's knowledge absorption level. The higher the ability of knowledge-sharing in the cross-border alliance to realize value transformation, the higher the income of both the principal and agent. In addition to the influence factors of the symbiosis environment, this paper adds some factors to the incentive model of knowledge-sharing, which reflect the willingness of the knowledge-sharing agent and the effort of the

principal to integrate innovation, as well as the knowledge gap that reflects the degree of cross-boundary cooperation between the parties. The research shows that a too large or too small knowledge potential difference are not conducive to the knowledge-sharing of the symbiotic system. Therefore, calculating the best advantage of the knowledge potential difference as well as defining a reasonable cross-boundary scope for the development of innovation cooperation can improve the cross-boundary innovation ability of the alliance and improve the sharing income of the symbiotic system. Both parties of the knowledge-sharing in the alliance are rational participants of risk aversion. Under the combined effect of the above factors, the sharing agent will determine the effort level and quality of knowledge spillover according to the incentive scheme by sharing the principal. The principal will also estimate the expected benefits and adjust the incentive scheme according to the knowledge-sharing efforts of the knowledge agent. Thus, the symbiotic game under the condition of information asymmetry is developed. Therefore, this paper's knowledge-sharing incentive model can provide an optimal incentive scheme for both the principal and agent in a symbiotic system.

(3) In this paper, we introduced the supervision mode of knowledge-sharing to reduce the information asymmetry between the principal and agent of knowledge-sharing. This is conducive to promoting knowledge-sharing and cross-boundary innovation cooperation activities. The multi-agent mechanism is introduced to indirectly improve the recognition degree of the knowledge principal to the knowledge-sharing effort level of the agent. Establish a supervision mechanism to ensure that the principal and agent of knowledge-sharing can judge each other's efforts more accurately. Taking the performance of the historical knowledge output of the principal and agent as a reference, through the combination of long-term incentives and short-term incentives, the sharing unit participating in the process of knowledge-sharing can reduce the speculative psychology and reduce the 'Ratchet effect' caused by information asymmetry.

Based on the research results of the knowledge-sharing incentive in the cross-boundary alliance symbiotic system, this paper further expands the theoretical research method of the principal–agent model and provides theoretical guidance for cross-boundary innovation cooperation among enterprises. The improved principal–agent model used in this study is very appropriate to reflect the symbiotic relationship of knowledge-sharing in cross-boundary alliances. Combined with the characteristics of the cross-boundary alliance, the model introduces relevant variables and reveals the operation mechanism of the principal–agent symbiotic game.

This research expects to provide some reference to solve the incentive problem of knowledge-sharing of the cross-boundary alliance. However, it seldom considers the impact of the position differences of cross-boundary alliance members in the symbiotic system and the influence of alliance members' different participation in the innovation process on alliance knowledge-sharing. There is no further empirical research through multiple groups of objective data. In addition, we only studied the knowledge-sharing process of two subjects in the alliance but the knowledge-sharing among the members of the cross-boundary alliance can also be a complex process with multi-party participation. Therefore, the principal–agent symbiosis of knowledge-sharing among multi-agents in cross-border alliances will be deeply discussed in order to find the best incentive strategy of multi-agent knowledge-sharing in future research. At the same time, the follow-up research will evaluate and provide feedback on the effect of knowledge-sharing, continuously improving the knowledge management level of cross-border alliances.

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## Appendix A

As mentioned in Section 3.2, we constructed the knowledge-sharing incentive model of cross-boundary alliances. The essential solution progress of the model is as follows.

The deterministic equivalent income of knowledge principal $CE_r$ can be calculated by Equation (A1).

$$\begin{aligned} CE_r &= E(\lambda_r) - F_r = E(\lambda_r) - \tfrac{1}{2}\rho_r D(\lambda_r) \\ &= (1-\beta)(\eta Kay - \alpha) - \tfrac{1}{2}b_r\eta^2 - \tfrac{1}{2}\rho_r(1-\beta)^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \end{aligned} \tag{A1}$$

The deterministic equivalent income of knowledge agent $CE_s$ can be calculated by Equation (A2).

$$\begin{aligned} CE_s &= E(\lambda_s) - F_s = E(\lambda_s) - \tfrac{1}{2}\rho_s D(\lambda_s) \\ &= \alpha(1-\beta) + \beta\eta Kay - \tfrac{1}{2}b_s a^2 - \tfrac{1}{2}\rho_s\beta^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \end{aligned} \tag{A2}$$

The principal–agent model of knowledge-sharing in Equation (19) can be calculated as follows:

$$\begin{aligned} &\max CE_r = (1-\beta)(\eta Kay - \alpha) - \tfrac{1}{2}b_r\eta^2 - \tfrac{1}{2}\rho_r(1-\beta)^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \\ &s.t.\begin{cases} (IC)\max CE_s = \alpha(1-\beta) + \beta\eta Kay - \tfrac{1}{2}b_s a^2 - \tfrac{1}{2}\rho_s\beta^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \\ (IR)\alpha(1-\beta) + \beta\eta Kay - \tfrac{1}{2}b_s a^2 - \tfrac{1}{2}\rho_s\beta^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \geq w_0 \end{cases} \end{aligned} \tag{A3}$$

According to the *IC* and *IR* rules, we acquire the knowledge-sharing willingness $a$. Under the Kuhn–Tucker condition, inequality *IR* equals sign holds. The principal–agent model can be transformed as follows:

$$\begin{aligned} &\max CE_r = (1-\beta)(\eta Kay - \alpha) - \tfrac{1}{2}b_r\eta^2 - \tfrac{1}{2}\rho_r(1-\beta)^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \\ &s.t.\begin{cases} (IC)a = \frac{\beta\eta yK}{b_s} \\ (IR)\alpha(1-\beta) + \beta\eta Kay - \tfrac{1}{2}b_s a^2 - \tfrac{1}{2}\rho_s\beta^2\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) = w_0 \end{cases} \end{aligned} \tag{A4}$$

Taking the *IC* and *IR* constraints into the objective function, we can derive the expression of $\max CE_s$. Take the first and second derivatives of $\max CE_s$ with respect to $\beta$ and $\gamma$, and we can derive that:

$$\begin{aligned} \frac{\partial CE_r}{\partial\beta} &= \frac{\eta^2K^2y^2}{b_s} - \frac{\eta^2K^2y^2\beta}{b_s} - \left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)(\rho_s\beta + \rho_r\beta - \rho_r) \\ \frac{\partial CE_r}{\partial\gamma} &= -\left[\rho_s\beta^2 + \rho_r(1-\beta)^2\right]\left(\gamma\delta_I^2 + \eta\mathrm{cov}(\pi, I)\right) \\ \frac{\partial^2 CE_r}{\partial\beta^2} &= -\frac{\eta^2K^2y^2}{b_s} - (\rho_s + \rho_r)\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right) \\ \frac{\partial^2 CE_r}{\partial\gamma^2} &= -\delta_I^2\left[\rho_s\beta^2 + \rho_r(1-\beta)^2\right] \end{aligned} \tag{A5}$$

Based on the above formula, the results of $\beta^*$ and $a^*$ can be derived as follows:

$$\begin{aligned} \beta^* &= \frac{\eta^2K^2y^2 + \rho_r b_s\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)}{\eta^2K^2y^2 + b_s(\rho_s + \rho_r)\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)} \\ &= \frac{K^2y^2\delta_I^2 + \rho_r b_s\left(\delta_H^2\delta_I^2 - \mathrm{cov}^2(\pi, I)\right)}{K^2y^2\delta_I^2 + b_s(\rho_s + \rho_r)\left(\delta_H^2\delta_I^2 - \mathrm{cov}^2(\pi, I)\right)} \end{aligned} \tag{A6}$$

$$\begin{aligned} a^* &= \frac{\beta\eta Ky}{b_s} = \frac{\eta Ky\left[\eta^2K^2y^2 + \rho_r b_s\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)\right]}{b_s\eta^2K^2y^2 + b_s^2(\rho_s + \rho_r)\left(\eta^2\delta_H^2 + \gamma^2\delta_I^2 + 2\eta\gamma\mathrm{cov}(\pi, I)\right)} \\ &= \frac{\eta Ky\left(K^2y^2\delta_I^2 + \rho_r b_s\left(\delta_H^2\delta_I^2 - \mathrm{cov}^2(\pi, I)\right)\right)}{b_s K^2y^2\delta_I^2 + b_s^2(\rho_s + \rho_r)\left(\delta_H^2\delta_I^2 - \mathrm{cov}^2(\pi, I)\right)} \end{aligned} \tag{A7}$$

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