Hindawi
Complexity
Volume 2024, Article ID 2940051, 13 pages
https://doi.org/10.1155/2024/2940051

Research Article

Identify the Critical Factors Influencing the Indexing Work of CoPS: A Multiagent Oriented Network Perspective

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Received 25 September 2023; Revised 29 February 2024; Accepted 6 April 2024; Published 30 April 2024

Academic Editor: Hiroki Sayama

The indexing work of complex products and systems (CoPS) is to determine a comprehensive set of indicators to ensure seamless integration of CoPS modules. Despite its pivotal role as a pioneering phase in CoPS development, indexing work has garnered relatively scant research attention. This paper explores CoPS indexing work through a network game model that considers a main manufacturer and several suppliers. The primary aim is to discern the key influencing factors affecting CoPS indexing work and elucidate the influence mechanism. Several interesting conclusions have been drawn: (1) subjective, environmental, and structural factors as the three key aspects influencing the CoPS indexing work network; (2) Subjective factors directly influence the agencies' selection of the optimal effort level for collaborative work, whereas environmental and structural factors indirectly impact their choice by affecting their network centrality; (3) the environmental factors within the indexing work network dictate the rate at which interagent interactions diminish with distance. To demonstrate and validate the research's findings, an examination of the indexing process of the China Lanxin High-speed Railway is conducted. This study offers new insights into CoPS indexing work, providing both theoretical references and practical suggestions for project teams to improve collaborative efficiency.

1. Introduction

Complex products and systems (CoPS) are high-cost, engineering-intensive constructs, encompassing networks, products, systems, constructs, and project portfolios, such as information systems, high-speed railways, commercial aircraft, and satellites [1, 2]. The typical approach to developing CoPS involves decomposing the product into individual systems. If these systems retain complexity, they are further broken down into smaller components [3]. Often, these systems or components are independently developed by separate companies. Ultimately, these diverse systems or components need to effectively couple together to constitute a CoPS. Therefore, at the inception of such systems or components development, it is crucial to establish a set of indicators (or criteria). These indicators not only facilitate the correct operation of each module but also enable the functional and structural integration of different modules, ensuring the CoPS performs as intended. Figure 1 illustrates this. For instance, during the early construction stages of the Lanxin High-speed Railway, to enhance the line's wind-resistant performance, a series of indicators had to be determined (including concrete mix ratio, sand mesh density, etc.) based on the entire line's potential impact from windy weather. The design, construction, and supervision of each construction section were executed under these indicators' guidance and specifications. They established a unified requirement for each construction section's windproof work and laid the groundwork for subsequent interface work, ensuring the perfect coupling of each construction section.

By leveraging established concepts in the current product architecture literature [4–7], we introduce the concept of indexing work, a collaborative task where different companies jointly design indicators to guide each company's development efforts, ensuring effective module coupling. Deep analysis on numerous CoPS development processes in China, including high-speed railway line constructions and power transmission and transformation projects, revealed that one

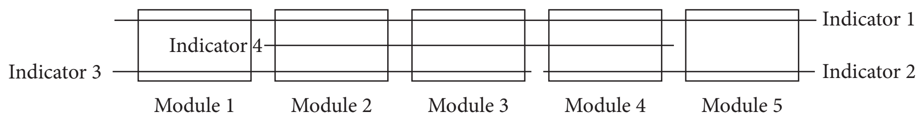

Figure 1: Various indicators ensure the seamless integration between different modules of CoPS.

of the most significant characteristics of CoPS indexing work is its networked nature. On one hand, each indicator is interconnected, forming a network. Any bias in the indexing work can lead to abnormal functioning in the corresponding modules, which can cascade into failures in the entire development work. On the other hand, indexing work often involves cross-organizational cooperation, creating a network of collaborative relationships. This networked nature renders CoPS indexing work extremely sensitive and fragile; even minor errors made by any participating company can disrupt the entire development process. This presents significant challenges to the incentivization and coordination of CoPS indexing work. Consequently, it becomes essential to analyze the CoPS indexing work from a network perspective.

However, most existing academic research on CoPS is focused on topics such as project work decomposition [8], cost control [9, 10], knowledge management [11, 12], and technical capability management [13, 14]. Studies adopting a network perspective to analyze CoPS indexing work are rare. To gain a deeper understanding of the CoPS indexing work, it is essential to analyze the influencing factors of the indexing work network and the interplay of mechanisms among these factors. This study will focus on three overarching research questions: (1) In CoPS indexing work, how do agencies affect each other's choices at their optimal effort level? (2) What is the impact of an agency's position in an indexing work on his (or her) optimal effort level? (3) What factors are suitable for effectively describing an indexing work of CoPS and how do these factors affect agencies' choice of their optimal effort level?

This paper formulates a multiagent network game model to investigate the determinants of CoPS indexing within the context of a social network. Throughout the process of CoPS indexing working, the principal frequently engages with multiple agents, sometimes constituting a substantial population. Interactions among these agents are anticipated to be pivotal in molding their behaviors. The CoPS indexing process encompasses not only linear principal-agent relationships between the primary manufacturer (the principal) and suppliers (the agents) but also network relationships emerging from interactions among agents. Consequently, the principal must not only consider the impact of the supervision and incentives on the decision-making behavior of agents but also contemplate the feasibility of an equilibrium resulting from interactions among the agents [15]. In this study, the model is grounded in a scenario characterized by the presence of a primary manufacturer alongside several suppliers. Within the dynamic interplay between the primary manufacturer and suppliers, a multi-agent principal-agent relationship crystallizes, comprising a solitary principal and a multitude of agents. These agents engage in collaborative endeavors aimed at delineating various indicators essential for fostering efficacious coupling across diverse modules. Confronted with the imperative of accomplishing the indexing work while concurrently optimizing their individual returns, agents face the challenge of selecting optimal effort levels, both in their independent and collaborative work. To govern and incentivize agent behavior, the main manufacturer orchestrates a judiciously devised fair allocation coefficient, thereby fostering motivation levels among agents and regulating cooperative interactions.

This paper is the first to model the index working of CoPS from the perspective of a network. I have solved the model and analyzed the impact factors of the index working, supplemented by a case study of the Lanxin High-speed Railway in China. The main results are as follows: (1) subjective, environmental, and structural factors as the three key aspects influencing the CoPS indexing work network; (2) Subjective factors directly influence the agencies' selection of the optimal effort level for collaborative work, whereas environmental and structural factors indirectly impact their choice by affecting their network centrality; (3) the environmental factors within the indexing work network dictate the rate at which inter-agency interactions diminish with distance. Higher values of these environmental factors result in a slower decay rate.

The remainder of this paper is organized as follows. Section 2 presents a literature review. Section 3 outlines the assumptions. Section 4 establishes models of CoPS indexing work from the perspective of network and analysis the companies' optimal decision-making. The case study of the Lanxin High-speed Railway is covered in Section 5. Lastly, Section 6 concludes this paper.

2. Literature Review

Two areas of research are related to this study: the development process of CoPS and social network analysis (SNA). CoPS is central to this study's discussion, and SNA is the main analysis method in this paper. We will then assess and contextualize comparably aligned studies within each respective area, as well as highlight the distinctions between this study and current literature.

The first line of research is concerned with the development process of CoPS. Due to the diverse expertise required in the development process of CoPS, which often involves collaboration among multiple companies, coordinating inter-firm relationships is typically a significant topic in the study of the development process of CoPS. Existing research on CoPS has mainly focused on the technical innovation process, paying less attention to the indexing work involved in the integration of various subsystems of CoPS. For instance, França et al. use a case study methodology to explore earlier stages of complex products and systems (CoPS) innovations, investigating how technology development can be coordinated [16]. From the perspective of the innovation ecosystem, Yang et al. analyzed the path for emerging economies to achieve catch-up results in CoPS outcomes [17]. Zhao et al. examined the impact of extrinsic and intrinsic rewards on knowledge sharing in complex product development, finding that intrinsic rewards positively influence both explicit and tacit knowledge sharing, while extrinsic rewards have a negative effect on tacit knowledge sharing [18]. Kim and Miles find that dynamic capabilities play a crucial role in developing system integration capabilities necessary for CoPS innovation [19]. Yu et al. investigate the impact of integrating artificial intelligence into complex products and systems, concluding that as CoPS emerges, a balance between generativity and criticality is crucial for transforming engineering management in CoPS contexts [20]. However, establishing a set of scientific and rational indicators is a crucial step in ensuring the effective integration of various subsystems to achieve the functional design of CoPS. This process involves collaboration among numerous stakeholders and exhibits a networked nature. Identifying the factors influencing this process is a vital prerequisite for establishing effective incentive mechanisms and coordinating the cooperation of all parties involved.

The escalating complexity of CoPS necessitates the confirmation of more indicators, thereby driving the demand for new research. Given this complexity, collaboration among diverse organizations, each contributing their own unique strengths, is inevitable. This frequent information exchange fosters a networked relationship among organizations, highlighting the need for SNA [21]. Initially proposed in the 1930s to study individual network characteristics and social relations [22], many SNA concepts have been extensively utilized in investigations on the CoPS production process. For instance, Dogan et al. employed SNA to examine the communication network of a large airport construction project [23]. Sosa et al. investigated the impact of the alignment between product architecture and organizational structure on CoPS development performance through static network analysis, leveraging SNA to define and quantify the modularity of CoPS components [7, 24]. Gokpinar et al. used SNA to analyze the relationship between the match of product architecture and organizational communication in CoPS, and product quality [25]. Liu et al. utilized SNA to trace the structural evolution of construction contractor cooperation in China from 2003 to 2010 [26]. Hossain and Wu employed SNA to analyze the relationship between network centrality and project coordination efficiency [27], while Son and Rojas used SNA to examine network efficiency, network stability, and network cohesion in engineering project construction [28]. However, existing articles on social network analysis primarily focus on analyzing the impact of network metrics on other factors [29], with limited emphasis on analyzing the behavior and decision-making of individual actors within the network.

This paper builds upon existing literature but takes an innovative approach by doing the following: discussing the CoPS indexing work in the perspective of network (unique to this study). Additionally, integrating game theory with SNA as a research methodology, this study analyzes the influencing factors in the standardization process of CoPS and explores the mechanisms of interaction among these influencing factors.

3. Assumptions and Notations

A company (main manufacturer) needs to produce CoPS (e.g., information system). In the production process, m indicators are determined by n companies or research institutions (collectively referred to as agencies). Each indicator is confirmed by a group of agencies that are led by an agency. Following the [30, 31], the main manufacturer and agencies are risk-neutral with a reservation profit of zero.

Company i is any agency in the network. In the process of indexing, he will exert independent work effort x_i to obtain and analyze experimental data and then get conclusions by himself. At the same time, he will exert a collaborative work effort y_i to work with other agencies to get some necessary data and conclusions. Both efforts x_i and y_i are private actions that are not contractible [32]. The indexing work is costly to both kinds of efforts. Due to the capacity of quadratic functions to aptly capture the rapid escalation of agents' effort costs with increasing effort levels, a characteristic highlighted in numerous studies exploring incentive mechanism design, this paper postulates that the cost associated with independent work effort, denoted as x_i, adheres to a quadratic form, specifically modelled as $x_i^2/2$, and the cost of collaborative work effort y_i is $y_i^2/2$ [33–35]. Let a_i denote the marginal output of the agency i's independent work, then the output of the agency i's independent work is $a_i x_i$ [36]. Denotes r the marginal output of the agency i's collaborative work with other agencies. The greater the value of r, the more output of agency i's collaborative work, the greater the need for collaborative work, and the more technical difficulty needs to be overcome [37].

Suppose the output of collaborative work between agency i and j is $a_i y_i + r g_{ij} y_i y_j$. In this context, $a_i y_i$ represents the output derived from the individual effort exerted by agent i in collaborative work, while $r g_{ij} y_i y_j$ signifies the joint output resulting from the combined efforts of agents i and j. The adoption of a multiplicative functional form for the latter is motivated by the consideration that, during collaborative endeavours, if the effort level of either party is 0, the overall collaborative output becomes null, reflecting the practical scenario where the output is contingent upon the active participation of all involved agents [37]. g_{ij} is a 0-1 variable. When there is a collaborative relationship between agency i and j, $g_{ij} = g_{ji} = 1$, otherwise, $g_{ij} = g_{ji} = 0$. Particularly, we stipulate $g_{ii} = 0$, i.e., there is no self-loop. Let matrix $\mathbf{G}$ (in bold) denote the adjacency matrix of the network of indexing work, $\mathbf{G} = (g_{ij})_{n\times n}$ [38]. The adjacency matrix $\mathbf{G}$ is a symmetric square matrix in which the diagonal elements are 0. Given that the indexing process of CoPS is susceptible to various uncertainties within the environment, similar to [39, 40], this paper designate ε_i as the environmental variable signifying the influence of external factors on the agency's output. Here, ε_i is characterized by a mean value of 0 and a variance of 1. Then, the output function of the agency i can be drawn as the function (1), where ε_i whose mean value is 0 and variance is 1 denotes the environment variable which indicates the impact of the external environment on the agency i's output.

$$\pi_i = a_i\left(x_i + y_i\right) + \sum_{j=1, j\neq i}^{n} r\, g_{ij} y_i\, y_j + \varepsilon_i. \tag{1}$$

The output function has been improved based on the research of [41, 42] and others. In their research, the main emphasis is on the influence of the behavior of the subject in the network (such as social networks) on others and does not involve the actors actively participating in other people's activities to influence their behavior. In other words, the "impact" they study is passive and unconscious. However, in the process of indexing work of CoPS, the interaction between the two cooperative agencies is active and conscious. The most prominent feature is that they will put in extra effort (y_i) to cooperate with other agencies. Therefore, this paper improves the research results of the above-mentioned people and gives the output function of equation (1)

The confirmation of the indicators requires the cooperation of multiple agencies. The main manufacturer considers the need to simultaneously motivate agencies' independent and collaborative work efforts when designing the incentive structure. Therefore, this paper draws on the incentive structure proposed by Kretschmer and Puranam [43] defines the compensation for agency i as.

$$S_i = \alpha \pi_i + \beta \sum_{j=1}^{n} \pi_j, \tag{2}$$

where α and β are parameters governing the incentive structure for the agency i. $\sum_{j=1}^{n} \pi_j$ represents the sum of all indexing work outputs. agency i gets paid purely on his leading indexing work if $\beta = 0$, and on overall indexing work outputs if $\alpha = 0$. Following the literature [38, 44], We restrict $0 < \alpha, \beta < 1$ so that the managers cannot be paid more than the total output. As a result, the α and β determine how much of agency i's incomes come from the agency i's leading work and the all indexing work.

Based on the above assumptions, we can derive the expected utility function of agency i as the function.

$$EU_i = \alpha \pi_i + \beta \sum_{j=1}^{n} \pi_j - \frac{1}{2} x_i^2 - \frac{1}{2} y_i^2. \tag{3}$$

In subsequent texts, bold symbols represent matrices, for example **G**, **X**, **Y**, and **I** represent different matrices.

4. Model Establishment and Analysis

4.1. Only Two Agencies Involved in the Indexing. In this subsection, we will study a benchmark case in which there are only two agencies (i and j) involved in the indexing work and they make decisions simultaneously. According to Section 2, the model, in this case, can be described as follows:

$$\begin{aligned}
&\max_{x_i, y_i} \mathrm{EU}_i = \alpha \pi_i + \beta\left(\pi_i + \pi_j\right) - \frac{1}{2} x_i^2 - \frac{1}{2} y_i^2, \\
&\max_{x_j, y_j} \mathrm{EU}_j = \alpha \pi_j + \beta\left(\pi_i + \pi_j\right) - \frac{1}{2} x_j^2 - \frac{1}{2} y_j^2, \\
&\text{s. t.} \begin{cases} x_i, x_j \geq 0, y_i, y_j \geq 0, \\ \mathrm{EU}_i, \mathrm{EU}_j \geq 0, \\ 0 \leq \alpha \leq 1, 0 \leq \beta \leq 1, \\ r \geq 0. \end{cases}
\end{aligned} \tag{4}$$

According to the solution method of the Nash equilibrium game

$$\begin{aligned}
x_i^* &= (\alpha + \beta) a_i, \\
y_i^* &= (\alpha + \beta) a_i + (\alpha + 2\beta) r y_j.
\end{aligned} \tag{5}$$

Proposition 1. *The stronger the agency i's ability, he is more likely to choose a higher level of independent work effort; the incentive structure (α and β) plays a positive role in the positive relationship between* x_i^* *and* a_i*, the higher the value of α and β, the stronger the positive relationship between the* x_i^* *and* a_i*.*

Proposition 2. *The optimal level of agency i's collaborative work effort* y_i *is positively related to his own ability* a_i *and the agent j's collaborative work effort* y_j*. The incentive structure and the CoPS' need for collaborative work (r) play a positive role in the positive relationship between* a_i*,* y_j^* *and* y_i^**, the higher the value of α, β, and r, the stronger the positive relationship.*

In the context of CoPS indexing work involving only two agents, Propositions 1 and 2 indicate that the effort exerted by agent i in independent tasks predominantly correlates with individual work capability and the incentive structure provided by the principal. In collaborative endeavors, this effort is not only linked to the agent's own work capability and the principal's incentive structure but is also influenced by the effort contributed by the collaborating partner throughout the collaborative process. It is noteworthy that, despite collaborating agent j's expected earnings being a component of agent i's expected earnings in the profit function, the equilibrium state reveals no direct association between agent i's collaborative work level and the work capability of collaborating agent j; instead, the direct impact is attributed to the effort level of collaborating agent j.

Evidently, a strategic incentive institutional design is imperative if principals aspire to elevate agents' effort levels in indexing work. For instance, to enhance agent i's effort level in independent work, considerations may include bolstering training programs to enhance the agent's work capability and concurrently refining the incentive structure to augment the agent's income. If principals seek to amplify agent i's effort level in collaborative work, a dual strategy is essential: enhancing the incentive structure to raise agent i's income level and developing measures to boost the effort level of their collaborative partner, agent j.

4.2. The Model of Indexing Work with n Agencies. When the indexing work involves n ($n \geq 3$) agencies, cooperation will form a network consisting of N subjects $N = \{3, 4, \cdots, n\}$ [45]. The model of the indexing work with n agencies is

$$\max_{x_i, y_i} \mathrm{EU}_i = \max_{x_i, y_i} \left(\alpha \pi_i + \beta \sum_{j \neq i}^{n} \pi_j - \frac{1}{2} x_i^2 - \frac{1}{2} y_i^2 \right),$$

$$\text{s. t.} \begin{cases} x_i \geq 0, y_i \geq 0, \\ EU_i \geq 0, \\ 0 \leq \alpha \leq 1, 0 \leq \beta \leq 1, \\ r \geq 0, \\ (\alpha + 2\beta) r < 1/\mu_{\max}(\mathbf{G}). \end{cases} \quad (6)$$

where the $\mu_{\max}(\mathbf{G})$ is the largest eigenvalue of $\mathbf{G}$.

We adopt Ballester et al.'s research result that when $(\alpha + 2\beta) r < 1/\mu_{\max}(\mathbf{G})$, the model will have a stable Nash equilibrium solution [38, 46]. Let the first derivative $\partial EU_i / \partial x_i = a_i(\alpha + \beta) - x_i = 0$, we can get $x_i^* = a_i(\alpha + \beta)$. Define column vectors $\mathbf{X}^* = [x_1^* \, x_2^* \, x_3^* \cdots x_n^*]^{\mathbf{T}}$ and $\mathbf{A} = [a_1 \, a_2 \, a_3 \cdots a_n]^{\mathbf{T}}$, then.

$$\mathbf{X}^* = (\alpha + \beta) \mathbf{A}. \quad (7)$$

According to $\partial EU_i / \partial y_i = 0$, the function of agency i's collaborative work effort level will be.

$$y_i^* = (\alpha + \beta) a_i + r(\alpha + \beta) \sum_{j=1, j \neq i}^{n} g_{ij} y_j + r\beta \sum_{j=1, j \neq i}^{n} g_{ji} y_j. \quad (8)$$

Define a column vector $\mathbf{Y}^* = [y_1^* \, y_2^* \, y_3^* \cdots y_n^*]^{\mathbf{T}}$, all the agencies' optimal collaborative work effort levels can be rewritten as.

$$\mathbf{Y}^* = (\alpha + \beta) \mathbf{A} + r(\alpha + \beta) \mathbf{G} \mathbf{Y}^* + r\beta \mathbf{G}^{\mathbf{T}} \mathbf{Y}^*, \quad (9)$$

where the $\mathbf{G}^T$ is the transposed matrix of $\mathbf{G}$. Because $\mathbf{G}$ is a symmetrical matrix, $\mathbf{G}^T = \mathbf{G}$, and

$$\mathbf{Y}^* = (\alpha + \beta)(\mathbf{I} - Q\mathbf{G})^{-1} \mathbf{A}, \quad (10)$$

where $\mathbf{I}$ is the $n \times n$ identity matrix. The comparison of equilibrium results is shown in Table 1. Compared with the situation of only two agencies, when N agencies participate in the indexing work, the effort level of each agency's collaborative work will be affected by the structure of the network of indexing work $(\mathbf{I} - Q\mathbf{G})^{-1}$. However, the effort level of independent work will be only affected by the agents' ability level. Further analysis may lead to the following conclusions.

Proposition 3. *(a) the level of independent work effort of agency i will not be affected by the other collaborative agencies, but is positively correlated with his own ability, and the incentive coefficients play a positive regulatory role in this positive correlation; (b) the level of collaborative work effort of agency i is positively correlated with the ability both of agency i and the incentive coefficients play a positive regulatory role in this positive correlation; beyond that, (c) the level of collaborative work effort of the agency i is positively correlated with the other agencies' collaborative work effort level, the incentive coefficients play a positive regulatory role in this positive correlation, which means with the enhancement of the agency i's ability, his optimal effort level will improve, and the degree of the improvement will increase with the increase of the incentive structure.*

It is easy to draw Proposition 3 according to (11) and (14). It is worth to note that agencies' ability is a considerable factor for an agency when he is choosing his independent work effort. As a result, we denote the agencies' ability as the subjective factor which is agencies' endogenous trait related to the effort level in the network of indexing work and has nothing to do with the external environment.

Combined with Propositions 1–3, it can be seen that the incentive coefficients (α and β) play a pivotal role in the cooperation of the agencies. The higher the incentive coefficients, the stronger the positive relationship between the agency's ability and their optimal effort level. Therefore, we define the incentive coefficients provided by the main manufacturer as the environmental factor of the indexing work. Unlike the subjective factor, the environmental factor is an exogenous variable that describes the environment in which the indexing work is located.

The above conclusions can bring about the following management implications. As Laffont mentioned in his classic The Theory of incentives: the principal-agent model, developing a higher incentive coefficient usually leads to a high level of effort, but a fixed incentive coefficient may also bring moral hazard problems. Therefore, if the incentive coefficient can be appropriately floated with the performance of the agency through some management method (such as carrying out various forms of labor competition), the agency can be better encouraged to work hard. On the other hand, as can be seen from Proposition 3(c), the choice of the agency's optimal level of collaborative work is influenced by the level of the collaborative effort of their partners. Therefore, it can be reasonably assumed that the final evolution of the level of collaborative work effort of all agencies usually has only two outcomes, either maintaining a higher level of effort or staying at a lower level of effort. Imagine an agency in the network of indexing work, directly or indirectly, he has a cooperative relationship with all other agencies. If his level of collaborative work effort has remained low, then the level of a collaborative effort of all agencies will tend to be lower, and vice versa. Therefore, to ensure that the level of collaborative work effort in the entire indexing work has been maintained at a high level, an important management measure is to make the important and influential agencies in the network always at a high level of effort.

Table 1: Comparison of calculation results.

Only two agencies in the indexing work		N agencies in the indexing work	
x_i^*	y_i^*	$\mathbf{X}^*$	$\mathbf{Y}^*$
$a_i(\alpha+\beta)$	$((\alpha+\beta)(a_i+a_jQ))/(1-Q^2)$	$(\alpha+\beta)\mathbf{A}$	$(\alpha+\beta)(\mathbf{I}-Q\mathbf{G})^{-1}\mathbf{A}$

Where $Q=(\alpha+2\beta)r$.

Proposition 4. *When environmental factors and subjective factors are certain, (a) the more the number of partners of an agency, the higher his network centrality; (b) the deeper the cooperation between the agency and the partners, the higher his network centrality.*

Denote $\mathbf{b}=[\mathbf{I}-(\alpha+2\beta)r\mathbf{G}]^{-1}$, When $(\alpha+2\beta)r>0$, there is

$$\mathbf{b}=[\mathbf{I}-(\alpha+2\beta)r\mathbf{G}]^{-1}=\sum_{k=0}^{+\infty}(\alpha+2\beta)^k r^k \mathbf{G}^k. \quad (11)$$

It can be seen that $\mathbf{b}$ is an n-th order square whose diagonal element is not 0, that is

$$\mathbf{b}=\sum_{k=0}^{+\infty}(\alpha+2\beta)^k r^k \mathbf{G}^k=\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}_{n\times n}. \quad (12)$$

Let $\mathbf{M}=\mathbf{b}\mathbf{1}_n$, where $\mathbf{1}_n$ is the n-dimensional vector of ones. Then there is

$$\mathbf{M}=[\mathbf{I}-(\alpha+2\beta)r\mathbf{G}]^{-1}\mathbf{1}_n=\begin{bmatrix} m_1 \\ m_2 \\ \vdots \\ m_n \end{bmatrix}, \quad (13)$$

where $m_i=\sum_{l=1}^{n} b_{il}$

It can be seen that the element m_i is only related to the incentive coefficients (α and β), the demand intensity (r) of the indexing work for cooperative work, the structure ($\mathbf{G}$) of the network of indexing work, and has nothing to do with the agency's own ability. The greater the value of m_i, the stronger the ability of agency i to influence other agencies. m_i is called the weighted Katz-Bonacich network centrality of agency i [38].

In the network represented by the adjacency matrix $\mathbf{G}=(g_{ij})_{n\times n}$, if any two nodes i and j are connected by one wire (that is, there are no other nodes in the middle), there is a path of length 1 between i and j. It means that there is a cooperative relationship between the agency i and j, and in $\mathbf{G}$, it is expressed as $g_{ij}=1$. If there is a path of length 2 between i and j, it means that there is another node, for example h, where $g_{ih}g_{hj}=1$. This means that agency i and j have a cooperative relationship with agency h, respectively. Denote b_{ij} as the ith row, jth column of $\mathbf{b}$, and then $b_{ij}=\sum_{k=0}^{+\infty}(\alpha+2\beta)^k r^k g_{ij}^{[k]}$ [41]. Where $g_{ij}^{[k]}$ denotes the ith row, jth column of $\mathbf{G}^k$ and represents the number of paths whose length is k between agency i and j, which reflects all the interactions between the two agencies in the network of indexing work. Due to $0<(\alpha+2\beta)r<1$, it can be seen that the farther the distance is, the weaker the mutual influence between the two agencies. For the agencies i and j, in the case of the same number of paths, the heavier the proportion of paths with larger lengths, the weaker the effect between them, and the smaller the value of b_{ij}. According to $m_i=\sum_{l=1}^{n} b_{il}$, we can see that another factor that determines the network centrality of an agency is the number of agencies he works with. The more agents he works with, the more network centrality he has in the network. So, the "quantity" and the "distance" are the basic elements that determine the network centrality of an agency in the network. Therefore, these two elements can be defined as a structural factor that describes the network of indexing work.

Proposition 5. *In the case of the same network structure of indexing work, increasing the values of α, β and r can make the agencies in the network more influential, and an agency's network centrality higher.*

It is easy to draw this conclusion based on $m_i=\sum_{l=1}^{n} b_{il}$. It can also be seen from equations (12) and (13) that the intensity of demand for CoPS indexing work on collaborative work (r) is an exogenous variable that affects the decision-making process of the agency's effort level. Like α and β, it is also an important factor in describing the environment of the network of indexing work. Therefore, r can also be defined as one of the environmental factors for the network.

Generally speaking, with the signing of the contract, the cooperation relationship between the agencies is determined, so does the network structure. If $\beta=0$, then there is no motivation for agencies to participate in collaborative work; If $r=0$, the collaborative work has no actual output. Conversely, if the values of β and r increase, the partnership in CoPS indexing work becomes even closer.

Proposition 6. *The environmental factors of the network of indexing work determine the speed at which the interagency interactions decay due to distance. The greater the value of the environmental factors, the slower the decay rate.*

The research results of Ballester et al. indicate that as the distance between two subjects in the network increases, the interaction between the two will gradually decrease. They use the "decay coefficient" to describe the trend [47]. Since their research focuses on analyzing the structure of the network and identifying key members, there is no specific discussion on the implications of this trend. It can be seen from the analysis of Proposition 4 that the reason for the decay is that the influence of environmental factors is gradually weakening as the distance between the two agencies increases. It can be seen that the connotation of the decay coefficient is the environmental factor of the network.

Proposition 7. *The stronger the network centrality of the agency, the higher the level of optimal effort for collaborative work he will choose.*

This conclusion can be easily drawn from (10). In the process of influencing the selection of agency companies' effort level, the influence mechanism of subjective factors is different from that of environmental factors and structural factors. The subjective factors directly affect the agencies' choice of the optimal effort level of collaborative work, while the environmental factors and structural factors affect the agencies' choice of the optimal effort level of collaborative work indirectly by affecting their network centrality.

Based on the above discussion, we can draw the influence of the subjective factors, environmental factors, and structural factors on the behavior pattern of the agency in the CoPS indexing work, as shown in Figure 2.

5. Case Study

This section undertakes a single-case study to scrutinize the practical implementation of indexing work in the construction process of the Lanxin High-Speed Railway, aiming to validate the applicability and reliability of the previously expounded theoretical analysis. The selection of the single-case study method is grounded in three principal considerations. Firstly, the analysis delves into the influencing factors and operational mechanisms within the CoPS indexing work, falling within the research domain encompassing "what" and "how." The adoption of a single-case study facilitates a more profound exploration of the contextual intricacies, enabling the in-depth investigation and deduction of influencing factors during the occurrence of events. It also aids in comprehending the operational mechanisms of each factor, thereby addressing questions related to "what" and "how" [48, 49]. Secondly, given the scarcity of existing research on CoPS indexing work and the relatively nascent state of current theories, this study aligns with the realm of exploratory research. In comparison to multiple case studies, the single-case study methodology is more conducive to exploratory cases. Through an in-depth analysis of representative cases, it allows the exhibition of processes and explication of relationships behind complex phenomena, facilitating the capture of developmental patterns with relevance to analogous phenomena [50]. Lastly, with theoretical model analysis having already delineated influencing factors and operational mechanisms within CoPS's indexing work, the purpose of the single-case study is to authenticate the reliability and applicability of the theoretical research conclusions. Therefore, the adoption of a single-case study is more congruent with the logical framework underpinning this study.

5.1. Background. Lanxin High-speed Railway from Lanzhou to Urumqi is a key project of China's Medium- and Long-term Railway Network Planning. Our research team conducted three investigations on the Lanxin Railway (Xinjiang) Co., Ltd. (Xinjiang Company) which is responsible for the construction management of Lanxin High-speed Railway in Xinjiang province and all the other companies or institutions involved in the construction. Through the collection and arrangement of relevant documents and archives, and the interview with the relevant persons in charge of the project, the research team has collected a lot of primary data.

The Lanxin High-speed Railway in Xinjiang province has been divided into 9 tenders during the construction process. Each tender encountered typical natural disasters such as hurricanes and sand damage in northwestern China. To ensure the smooth progress of the project construction, Xinjiang Company (the main manufacturer) organized construction enterprises, designing institutions, and universities (the agencies) to confirm a series of indicators. Part of the cooperative network between these companies and institutions is shown in Figure 3.

5.2. Analysis. To ensure the smooth progress of the indexing work, the Xinjiang company has formulated a series of management measures. These management measures are usually sent to agencies in the form of notifications. By reading and organizing these notification files, we were able to restore these management practices. Many management methods or concepts are consistent with the three major impact factors mentioned in this article.

5.2.1. Subjective Factor. The Xinjiang Company chooses and continuously improves the ability of the agencies in two ways: prequalification and training. In a document called the Notice on Printing and Distributing "the Management Manual for the Standardization Construction of Lanxin High-speed Railway (Xinjiang section)," it is stipulated that the bidding enterprises need to be prequalified to ensure that they meet all the conditions. The prequalification can ensure that the ability of the winning bidders is at a high level. There are also a large number of notices about training. By sorting out these documents, we learned that during the construction period, the Xinjiang Company held 29 management and professional technical training courses, training more than 4,000 person-times.

The essence of the prequalification and training courses is to manage the network of indexing work by influencing the subjective factor. This is consistent with the conclusion 1, 2, and 3.

5.2.2. Environmental Factor. The indexing work of the Lanxin High-speed Railway is well managed by the appropriation system. "Funding must be managed by the financial department of the institution that leads the indexing work, and appropriate allocations should be made according to the budget and project progress," "the company may suspend or stop the appropriation for the failure to submit the project execution schedule according to the specified time." The essence of the appropriation system is that the incentive coefficient keeps fluctuating as the project progresses. When the indexing work achieves a staged result and gets the acceptance of Xinjiang Company, the funding of the

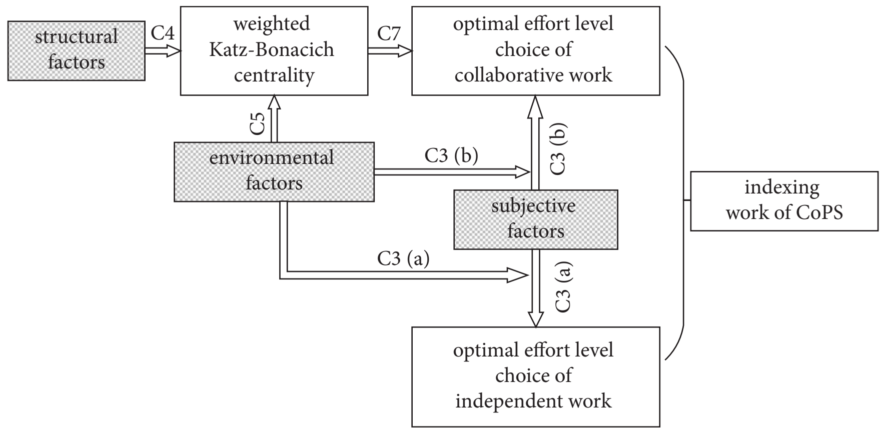

Figure 2: The influence mechanism in the network of indexing work.

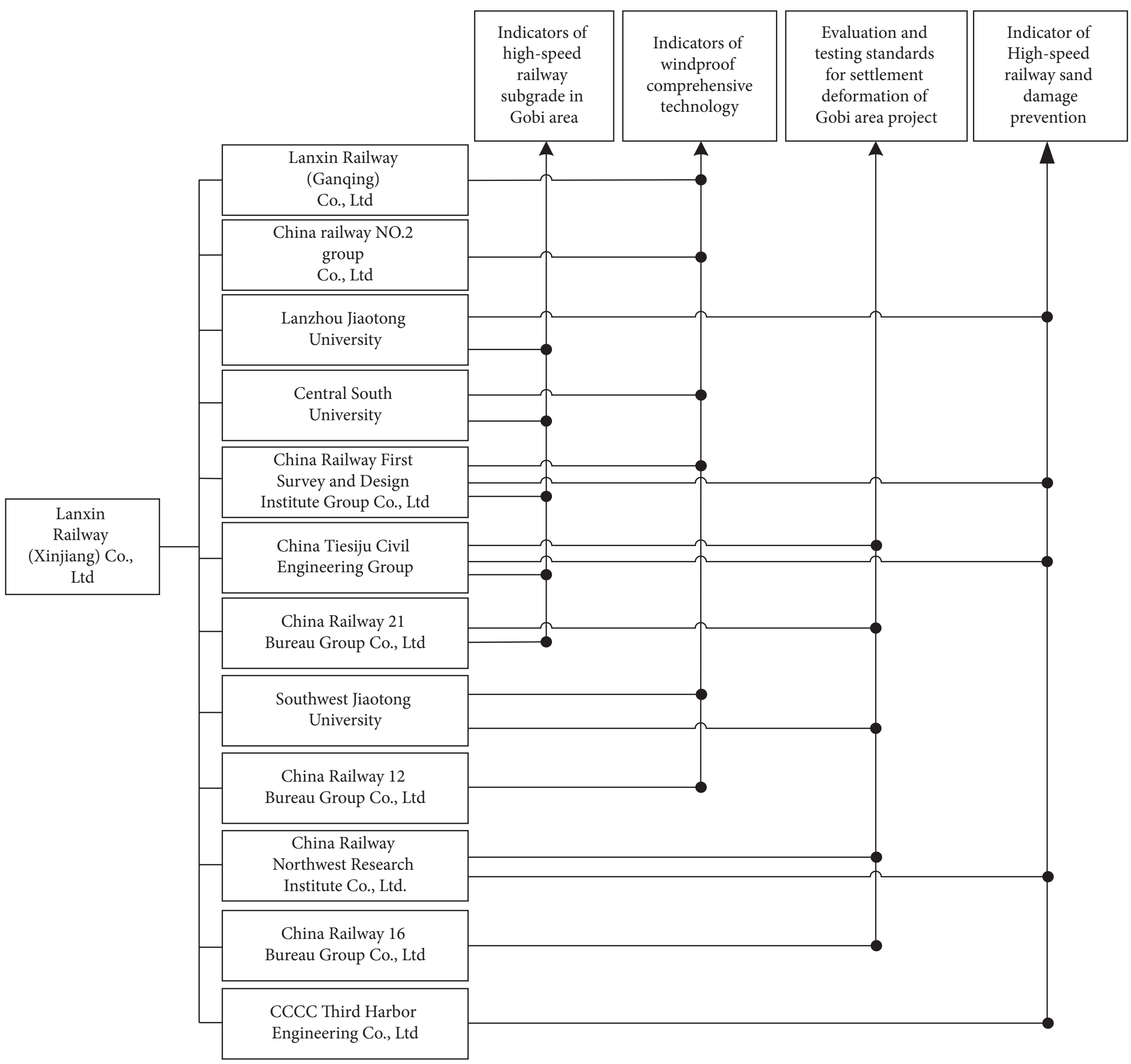

Figure 3: Part of the cooperative network relationship in the lanxin high-speed railway.

next stage will be obtained. As the funding for research increases, the incentive coefficient for indexing companies is also increasing—at the beginning, it may be only 30% of the indexing funding; after the mid-term inspection it may be 50%; and finally, when the indexing work is completed, 100% of the entire research funding will be obtained. It can be seen that Xinjiang Company's management measures in the indexing work coincide with the impact mechanism between the incentive coefficient and the agency companies' choice of indexing work effort level, which is proposed in Conclusion 3.

Through interviews with relevant staff of the Scientific Research Management Office of Xinjiang Company, the research team found out that whether it is reward or punishment, the company's management methods for each institution are based on the two indicators α and β—"Only based on the money, rewards and punishments are more effective," a staff mentioned. Some staff members also pointed out that for the indexing work, which is difficult and involves a large number of organizations, it is usually the focus of their monitoring. Companies engaged in such indexing work usually have higher returns, but in the event of an accident, they are subject to more severe penalties. It can be seen that α, β and r are critical for the management work and determine the environment of the network of indexing work. This is consistent with the conclusion 4.

5.2.3. Structural Factor. To analyze the influence of network structure factors on the indexing work of the Lanzhou-Xinjiang High-speed railway, the network structure shown in Figure 3 needs to be depicted by matrix first. Let A, B, C, . . ., K, L represent Lanxin Railway (Ganqing) Co., Ltd; China railway NO. 2 group Co., Ltd; Lanzhou Jiaotong University; . . .; China Railway Northwest Research Institute Co., Ltd; CCCC Third Harbor Engineering Co., Ltd and other 12 companies in Figure 3, respectively. When there is a partnership between two companies, it is represented by 1, and when there is no partnership between two companies, it is represented by 0. For example, when determining the indicators of high-speed railway subgrade in the Gobi area, Central South University (D) and Lanzhou University (C) have a cooperative relationship, so the relationship between them is represented by 1. D did not take part in all the indexing work participated by China Railway Northwest Research Institute Co., Ltd. (J). At the same time, J did not participate in the indexing work of D, so there was no cooperative relationship between D and J, which was represented by 0. In the same way, the partnership of 12 companies can be sorted out, and the matrix in equation (14) can be obtained. The first row (or first column) in the matrix represents the Lanxin Railway (Ganqing) Co., Ltd, the second row (second column) represents the China railway NO. 2 group Co., Ltd, and so on. Besides, α, β and r are assigned, as shown in Table 2.

The higher the centrality, the more work the company participates in and plays a more important role in the indexing work of CoPS. From the calculation result (15), we can see that CCCC Third Harbor Engineering Co., Ltd has the least centrality and its value is 1.8572; China Railway First Survey and Design Institute Group Co., Ltd has the largest centrality and its value is 2.9393. As shown in Figure 3, CCCC Third Harbor Engineering Co., Ltd has only participated in one indicator confirming work and has direct cooperation with only five other companies, however, China Railway First Survey and Design Institute Group Co., Ltd has participated in three projects and has direct cooperation with nine other companies. The centrality of model calculation can accurately reflect this reality.

By comparing the work of CCCC Third Harbor Engineering Co., Ltd and China Railway First Survey and Design Institute Group Co., Ltd in the construction of Lan-Xin high-speed Railway, it can be found that the latter with higher centrality has indeed made a higher level of efforts, even in the confirmation of indicators of high-speed railway sand damage prevention, the latter is higher than the former in personnel training equipment investment and other aspects. Therefore, a higher centrality does lead to a higher level of effort on the part of the agency. This comparison supports conclusions 5, and 7 from the side.

$$\mathbf{G} = \begin{array}{c} \\ A \\ B \\ C \\ D \\ E \\ F \\ G \\ H \\ I \\ J \\ K \\ L \end{array}\!\!\begin{array}{c} \begin{array}{cccccccccccc} A & B & C & D & E & F & G & H & I & J & K & L \end{array} \\ \left[\begin{array}{cccccccccccc}
0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 \\
1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0
\end{array}\right] \end{array}. \tag{14}$$

It can be obtained that the Katz-Bonacich network centrality of each company in the network in this case is (15)

Table 2: The assignment of α, β and r.

α	β	r
0.05	0.01	1.2

$$\mathbf{M} = [\mathbf{I} - (\alpha + 2\beta)r\mathbf{G}]^{-1}\mathbf{1}_n = \begin{bmatrix} 1.0621 & 0.1396 & 0.0404 & 0.1510 & 0.1562 & 0.0542 & 0.0523 & 0.1531 & 0.1396 & 0.0425 & 0.0254 & 0.0246 \\ 0.1396 & 1.0621 & 0.0404 & 0.1510 & 0.1562 & 0.0542 & 0.0523 & 0.1531 & 0.1396 & 0.0425 & 0.2539 & 0.0246 \\ 0.0404 & 0.0404 & 1.0776 & 0.1487 & 0.1708 & 0.1650 & 0.1548 & 0.0807 & 0.0404 & 0.1535 & 0.0465 & 0.1316 \\ 0.1510 & 0.1510 & 0.1487 & 1.1106 & 0.1983 & 0.1671 & 0.1632 & 0.1868 & 0.1510 & 0.0810 & 0.0502 & 0.0500 \\ 0.1562 & 0.1562 & 0.1708 & 0.1983 & 1.1454 & 0.1915 & 0.1805 & 0.2036 & 0.1562 & 0.1761 & 0.0631 & 0.1414 \\ 0.0542 & 0.0542 & 0.1650 & 0.1671 & 0.1915 & 1.1121 & 0.1789 & 0.1787 & 0.0542 & 0.1766 & 0.1383 & 0.1382 \\ 0.0523 & 0.0523 & 0.1548 & 0.1632 & 0.1805 & 0.1789 & 1.0969 & 0.1746 & 0.0523 & 0.1662 & 0.1358 & 0.0571 \\ 0.1531 & 0.1531 & 0.0807 & 0.1868 & 0.2036 & 0.1787 & 0.1746 & 1.1264 & 0.1531 & 0.1642 & 0.1381 & 0.0527 \\ 0.1396 & 0.1396 & 0.0404 & 0.1510 & 0.1562 & 0.0542 & 0.0523 & 0.1531 & 1.0621 & 0.0425 & 0.0254 & 0.0246 \\ 0.0425 & 0.0425 & 0.1535 & 0.0810 & 0.1761 & 0.1766 & 0.1662 & 0.1642 & 0.0425 & 1.0928 & 0.1344 & 0.1343 \\ 0.0254 & 0.0254 & 0.0465 & 0.0502 & 0.0631 & 0.1383 & 0.1358 & 0.1381 & 0.0254 & 0.1344 & 1.0459 & 0.0321 \\ 0.0246 & 0.0246 & 0.1316 & 0.0500 & 0.1414 & 0.1382 & 0.0571 & 0.0527 & 0.0246 & 0.1343 & 0.0321 & 1.0458 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$= \begin{bmatrix} 2.0410 & 2.0410 & 2.2504 & 2.6088 & 2.9393 & 2.6090 & 2.4649 & 2.7651 & 2.0411 & 2.4066 & 1.8606 & 1.8572 \end{bmatrix}^T. \quad (15)$$

6. Conclusions and Managerial Implications

6.1. Conclusions. In the development process of CoPS, the primary focus is to initially establish unified performance parameters for each subsystem. The standardization of indicators involves numerous participating entities collaborating with each other. Not only are these entities responsible for completing the indicator standardization for their respective subsystems, but they also participate in the work of other subsystem leaders, assisting them in the formulation of indicators. Therefore, the networked collaboration among participating entities is a prominent feature in the process of CoPS indicator formulation. Existing literature has provided limited research on the standardization of indicators for CoPS. This paper innovatively integrates social network theory and principal-agent theory to formulate a network game model, which is applied to examine influential factors and their mechanisms that impact the collaborative network in CoPS indexing. The study reveals that subjective, environmental, and structural factors are three pivotal elements characterizing the CoPS indexing work network. These elements significantly influence the behavioral patterns of agencies involved.

Subjective factors relate to the ability of agencies involved in the indexing work, exhibiting a positive correlation with the optimal level of effort chosen by these agencies. Environmental factors, on the other hand, pertain to the incentive framework established by the primary manufacturer and the degree of demand for collaboration in the indexing tasks. Lastly, structural factors encompass the quantity of business partners involved in the indexing work and the magnitude of cooperation between enterprises. As these factors increase, the company is inclined to select a higher level of effort, thereby intensifying the cooperation. Environmental factors play a constructive regulatory role in the process where subjective and structural factors shape the company's choice of behavior.

6.2. Managerial Implications. The research findings of this paper can offer management recommendations to principal manufacturers engaged in the CoPS indexing work, particularly from the perspective of incentive mechanism design.

(1) For principals aiming to enhance the independent effort level of agents, it is advised to consider the subjective factor as a crucial element. Providing agents with more training or communication opportunities to elevate their working capabilities proves to be highly effective, as indicated by the research conclusions. The effort level of agents in independent work is positively correlated with their own working capabilities. The augmentation of training and facilitation of interenterprise communication would enhance the overall working capabilities of the enterprise, consequently raising the effort level of agents.

(2) For principals desiring an increased effort level of agents in collaborative work, it is recommended to prioritize environmental factors and employ incentive mechanisms as leverage. The research findings reveal that the effort level of agents in collaborative work is influenced by the incentive structure and the effort level of collaborating units, with a positive correlation between the incentive structure and the effort level of collaborating units. Thus, the implementation of a well-designed incentive structure can stimulate the effort level of

collaborating units, thereby augmenting the effort level of other collaborating units in collaborative work.

(3) It is suggested that principal manufacturers incorporate the concept of network analysis into the contract management process. The research in this paper highlights structural factors as crucial elements influencing CoPS indexing work. Therefore, during contract management, principal manufacturers can generate cooperation network diagrams among different agents based on contract relationships. By calculating the Katz-Bonacich network centrality of each agent, higher incentive levels can be assigned to agents with elevated Katz-Bonacich network centrality, thereby fostering cooperation enthusiasm among other agents.

6.3. Limitations and Future Research Directions. While this paper provides valuable insights for the CoPS indexing work, it does have acknowledged limitations. Firstly, a static and linear incentive structure is primarily analyzed in this study. Although such a structure is commonly adopted in the literature on incentive mechanism design, various incentive forms between the principal manufacturer and agents, such as profit-sharing or competitive tournaments, may exist in real-world scenarios. The exploration of diverse incentive measures and the conduct of a horizontal comparative analysis could potentially reveal more nuanced research conclusions. Additionally, the assumption of complete rationality among all involved entities—the principal manufacturer and the agencies—is made in this research, constituting a strong assumption. Decision-makers, influenced by bounded rationality factors like overconfidence, fairness preferences, reciprocity, altruism, among others, may deviate decisions from optimality in practice. Extra attention is necessitated when applying the study's findings in real-world situations. Finally, the case study in this paper adopts a single-case study approach. Despite being the world's longest high-speed railway completed in a single phase, the indexing work of the Lanxin High-Speed Railway holds significant representativeness in the in the development process of CoPS, especially in the domain of linear engineering. However, it is crucial to note that the research conclusions may require adjustments when applied to management practices in other complex product contexts, depending on specific circumstances.

There are numerous possibilities for future study. A natural extension involves considering different forms of interaction among agents. In real-world scenarios, agents engaged in CoPS indexing work exhibit not only cooperative relationships but also competitive ones. Exploring the decision-making of agents in a competitive environment and designing more rational incentive mechanisms for principals may yield more intriguing results. Another extension pertains to the consideration of bounded rationality. Individuals do not consistently make optimal decisions in uncertain environments. Therefore, the incorporation of any form of bounded rationality into this model could provide further insights.

Data Availability

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

This paper was partially supported by the Science and Technology Foundation for Transportation of Shaanxi Province [No: 21-33R, 23-07R] and Shaanxi Province Philosophy and Social Science Research Special Youth Program [No: 2024QN033].

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