Hindawi
Scientific Programming
Volume 2023, Article ID 3372820, 10 pages
https://doi.org/10.1155/2023/3372820

Research Article

Grey Interest Chain Identification and Control Model for Government Investment Engineering Projects Based on Node Identification

Lin Deng,[1] **Yaping Wu**,[2] **Xianjun Chen**,[3] **Tian Li**,[3] **and Yun Chen**[3]

[1]*Hunan Communication Polytechnic, Changsha 410000, Hunan, China*
[2]*Guangdong International Consulting Ltd., Guangzhou, Guangdong 510000, China*
[3]*School of Traffic & Transportation Engineering, Changsha University of Science and Technology, 410000, Changsha, Hunan, China*

Correspondence should be addressed to Yun Chen; cheny@csust.edu.cn

Received 28 April 2023; Revised 18 July 2023; Accepted 27 October 2023; Published 14 November 2023

Academic Editor: Debo Cheng

In the bidding process of government investment engineering projects, collusion between the government and bidders occurs repeatedly, which seriously affects the quality of engineering projects and the effectiveness of the government investment. Therefore, it is necessary to analyze and discuss the collusion between the government and bidders in government investment engineering projects, so as to provide a healthy and sustainable environment for the government investment engineering bidding market. There are two main types of collusion in engineering bidding: horizontal collusion and vertical collusion, and this paper focuses on the vertical collusion process in the engineering bidding process. A conceptual framework of the grey interest chain based on three stages of benefit creation, benefit distribution, and benefit realization was established, 15 major nodes in the grey interest chain were identified, and a grey interest chain control model was constructed, which further identified and classified the nodes into four levels: key nodes, important nodes, general nodes, and unimportant nodes. Finally, through the application of the model in the case, measures such as establishing a cracking mechanism for grey resource integration, increasing the supervision of grey interest chain, and strengthening post-bid audit are proposed. Measures such as including the preparation of bidding documents into the work assessment system and entrusting consulting units or third parties to prepare bidding documents are proposed to establish a crack mechanism for grey resource integration. In the benefit distribution stage, the penalties for the government and the bidders can be appropriately increased, the responsibilities of enterprises and project leaders can be implemented in the system on a reciprocal basis, and a perfect reputation mechanism information can be established. At the stage of benefit realization, the bidding system should be improved and post-bid audit should be strengthened to increase the difficulty of grey benefit realization. This paper will provide a reference for the prevention and governance of vertical collusion in bidding and tendering.

1. Introduction

The collusion of various interest subjects in the bidding of engineering projects is a common economic and social phenomenon in the field of engineering [1]. In the field of bidding for government investment projects, the government is the central person of interest in the project, and the bidder is the claimant of the bidding information, and the two form the relationship between supply and demand, so their collusion problem is also the most prominent. As the scale of government-invested projects increases, collusion between the government and bidders tends to become more concealed and complicated, leading to lower quality of works and lower efficiency of the government [2]. Vertical collusion in the bidding makes the bidding information obtained between bidders unequal, which damages the legitimate rights and interests of other bidders and disrupts the normal bidding order, causing disorder, and a crisis of confidence in the bidding market.

Relevant research on bidding and tendering collusion gradually from horizontal collusion to vertical collusion and to the bidder and the bidder collusion problems. Since the promulgation of the bidding law, the bidding market has tended to develop more and more in the direction of fairness, impartiality, and openness, but at the same time, there are also a lot of subtle problems that have not been well-solved and controlled, so that the problem of bidding collusion still exists. Against the background of the increasingly serious problem of collusion, the study of collusion in bidding for government investment projects faces two major problems. First, through what channels is collusion between government and bidders formed and manifested? This paper first starts from three stages of interest creation, interest distribution, and interest realization, puts forward the basic concept and formation framework of grey interest chain between government and bidders in the government investment engineering projects, and elaborates the main formation process of grey interest chain between government and bidders. Second, after clearly understanding the formation process of interest chain, how to identify the influencing factors in the collusion process and control them? This paper considers this issue, constructs a grey interest chain control model to identify the key nodes in the interest chain, and formulates corresponding node control measures based on the identification results. The contributions of the study focus on the following two points:

(1) Theoretical contribution: the conceptual model of grey interest chain between government and bidders and the control model of grey interest chain are proposed, which enriches the research connotation of collusion in bidding for government investment engineering projects and lays a solid theoretical foundation for the subsequent extended research.
(2) Practical contribution: the application of specific cases provides reference solutions for the governance of vertical collusion behavior in the engineering bidding, which is conducive to regulating the functions, responsibilities and roles of government, bidders, and other interest subjects in engineering bidding management, so as to improve the quality and efficiency of government-invested engineering projects.

The main research work of the thesis is as follows. In the second part, through reviewing and sorting out the domestic and foreign literature, the current status of research on the issue of bid collusion is understood. In the third part, a conceptual framework of the grey interest chain between the government and bidders in the government investment projects is built, and a grey interest chain control model is constructed for node identification and hierarchy classification. In the fourth part, a specific typical case is used as the background to obtain the importance level of each node of the grey interest chain. In the fifth and sixth parts, targeted governance measures are proposed, pointing out some of the current problems of the thesis and the areas that should be explored in depth in the future.

2. Literature Review

In the bidding activities of engineering projects, there are two main types of collusion. One is vertical collusion in tendering, which means that the main person in charge within the tender covets the illegal gains promised by the bidder and is in league with the potential winning bidder. The second is horizontal collusion between bidders, which means that the intended bidders form a bidding alliance and collude in the pricing of the project, ultimately allowing one party to win the contract [3]. At present, a great deal of research by scholars on the issue of vertical collusion in tendering for engineering projects has focused on the following three aspects.

The first is the study of the causes of collusion. In the bidding process of engineering projects, the concealment and nondetectability of collusion have gradually increased due to the large number of interest-related subjects and the complexity of the bidding process, and the identification of the causes of collusion has become a recognized international problem.

Using big data, Abrantes-Metz and Bajari [4] suggested that the main reason for the high incidence of vertical collusion was the absolute new ownership of information by the bidders. Kadalbajoo and Gupta [5] found that in addition to information asymmetry, the pursuit of additional benefits also contributed to collusion in the bidding process. Miklós-Thal [6] argued that in the absence of additional costs, collusion is likely to occur between project bidding stakeholders regardless of whether the costs of vertical collusion are symmetrical, and that collusion is more likely to occur when the costs of collusion are symmetrical, but can be facilitated when additional costs are present [6]. Burguet and Perry [7] constructed a corruption model to analyze the impact of collusive supplier bribery and cost distribution on procurement auction mechanisms and found that when the pursuit of revenue by auctioneers increased, so did corrupt practices. Zheng [8] explored the conditions necessary for collusion to arise in the tendering of construction projects, including the status of bids, competitive procedures, and the level of regulation. Wang et al. [9] explored the combined effects of three external environmental factors—economic, industrial, and geographical—on bid collusion decisions through 254 cases of bid collusion in the Chinese construction industry. The results show that industrial competition positively affects bidders' willingness to collude and the number of collusion teams, and the coupling of economic development and industrial competition positively affects bidders' collusion prices [9].

The second is a study of the manifestations of collusion. Lee and Hahn [10] conducted an empirical study on bid-rigging and deduced from statistical evidence that in cases where bidders and bidders collude, there are often late supplementary agreements between the colluding parties, resulting in the final total project work being much higher than the bid price. Signor et al. [11] used a probabilistic and statistical approach to identify nonnormally distributed tender offers, thereby detecting collusive behavior. At the same time, the expected behavior of disobedient bidders was compared to identify collusive behavioral characteristics based on a summary of the 187 highest price auction patterns [12]. Kwasnica and Sherstyuk [13] discussed behavioral rules in multiunit auctions. In the process of collusion in bidding for the government investment projects, it is usually manifested in bid rigging, bid collusion, bid evaluation expert collusion, project splitting, and bid avoidance. Pesendorfer [14] stated that the two main ways of tenderer-bidder collusion were compensation and subcontracting. Nie et al. [15] classified the collected collusion cases through systematic clustering and conducted social network analysis to explore the characteristics and patterns of the types of collusion behavior of bidders. Through interviews, Bowen et al. [16] found that collusion in the South African construction industry manifested itself in the form of bribery, disinformation, and unfair competition. Yun et al. [17] analyzed the main nodes of each link according to the bidding process and used evidentiary reasoning to conclude that the main forms of collusion in bidding are the setting of biased review clauses, the preparation of biased bidding documents, and the implicit intervention of the bidders in bid evaluation. Aoyagi [18] derived equilibrium conditions for collusion between bidders and analyzed the distribution of benefits from the collusion.

The third is a study of collusive governance measures. Huber and Imhof [19] took a combination of statistical and machine learning approaches to discriminate the distribution of bids in tenders through model training and optimized the governance solutions of the institutions involved through the processing of false positive and false negative predictions. Zhu et al. [20] established a comprehensive evaluation model based on deep neural networks and migration learning to mine collusion features of tender-related subjects from a limited set of hidden data and assess collusion tendencies for an effective diagnosis and monitoring of vertical collusion in construction project tenders. Rodríguez et al. [21] believed that collusion was a widespread phenomenon in the public sector procurement. In his research, he obtained collusion datasets from Brazil, Italy, Japan, Switzerland, and the United States and tested the accuracy of 11 machine learning algorithms used to detect collusion. Ma et al. [22] constructed a four-way evolutionary game model based on a prospect theory with bidders, firms with a higher willingness to collude, firms with a lower willingness to collude, and supervising firms, concluding that higher project base returns increase the likelihood of collusion, while lower market competition, higher risk aversion, and stronger regulation reduce collusion. Sohail. and Cavill [23] pointed out the importance of strengthening the accountability of stakeholders, improving their respective responsibilities and effectively fulfilling their obligations to prevent complicity. Van Den Heuvel [24] analyzed the characteristics of vertical collusion in bidding, combining a genetic algorithm to trace back bidding subjects and followers to inhibit the willingness of bidding stakeholders to collude. Other scholar also used some basic algorithms to evaluate a nexus between inputs and output [25, 26].

In summary, although the academic community has conducted in-depth research on bidding collusion and achieved more research results, providing theoretical methods for the identification and control of bidding collusion, only very few scholars have conducted research on the formation process of bidding collusion from a systematic perspective. Therefore, this paper explores the formation process of vertical collusion in bidding in conjunction with the concept of grey interest chain, the grey interest chain control model can identify or detect the key nodes in the interest chain, and these key nodes should be disrupted or neutralized by implementing control measures to better manage the bidding collusion problem.

3. Method

The research framework of this paper is briefly described as follows: first, the basic conceptual framework of the grey interest chain is constructed, and the formation process of the grey interest chain of the government and the bidders is analyzed, second, the preselected node set of the grey interest chain is formed by sorting and summarizing the literature, and the main nodes are identified after screening and identification. Finally, based on the parameterized design, control node identification and grading, the control model of the grey interest chain is established, and the nodes in the grey interest chain are classified according to their importance, and different control measures are proposed, and the specific steps of the analysis are shown in Figure 1.

3.1. Analysis of the Formation Process of the Grey Interest Chain

3.1.1. Conceptual Framework. The grey interest chain refers to the act of power (money flow) in which relevant interest subjects form a relatively stable relationship in order to achieve common interests, in violation of the rules of fair competition in the market, with the right subjects providing information resources for trading (information flow) and achieving collusive goals in order to obtain huge benefits. The grey interest chain between the government and bidders mainly includes three links: benefit creation, benefit distribution, and benefit realization. The creation of benefits is the basis for the formation of the interest chain, the balanced distribution of benefits is the guarantee for the continuity of the interest chain, and the realization of benefits is the final expression of the benefits gained. Therefore, the government and the bidders in the government investment projects must first have the motivation, ability, and favorable factors to create interests before talking about the distribution and realization of interests. To explore the grey interest chain between the government and bidders in the government investment engineering projects, we need to take the interest creation stage as the starting point and analyze its formation reasons and process, as shown in Figure 2.

3.1.2. Node Preselection. The grey interest chain between the government and the bidder is made up of three stages, including benefit creation, benefit distribution, and benefit realization. In the benefit creation stage, there are three main links, including relationship construction, relationship interaction, and relationship formation. The benefit distribution stage includes the link of benefit scheme setting. The benefit realization stage includes the link of winning measures. The links contain various specific behaviors, motivations, and considerations of the government and the bidders, which we call nodes, that is, the behavioral influences or the way they behave in each

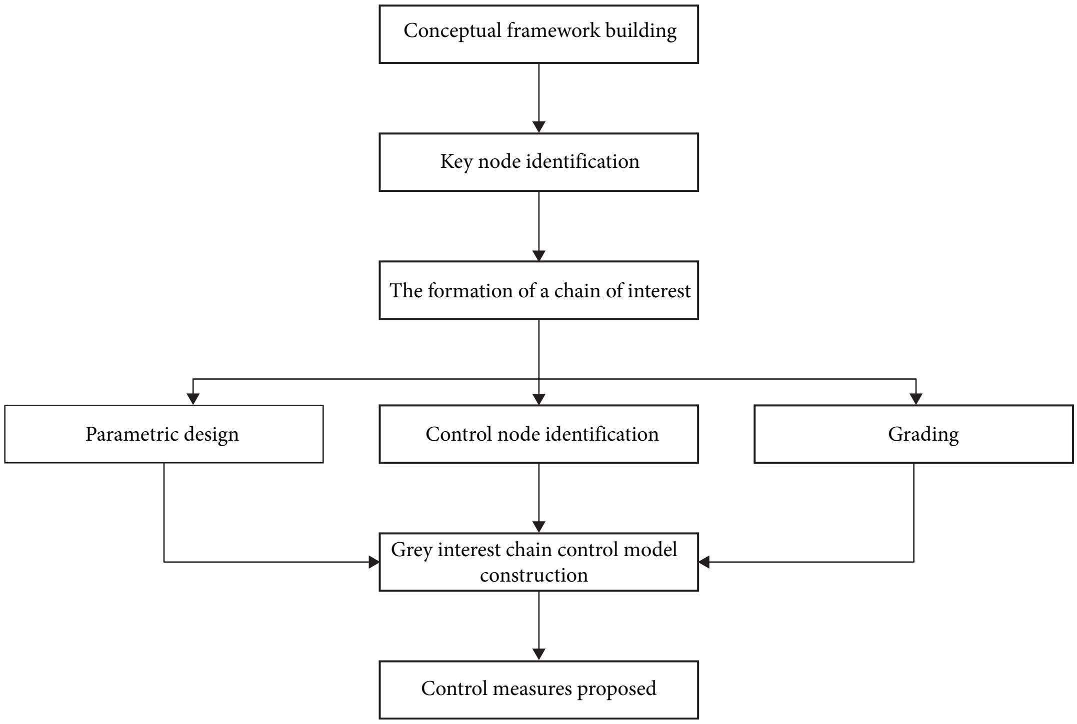

Figure 1: Analysis process of the model.

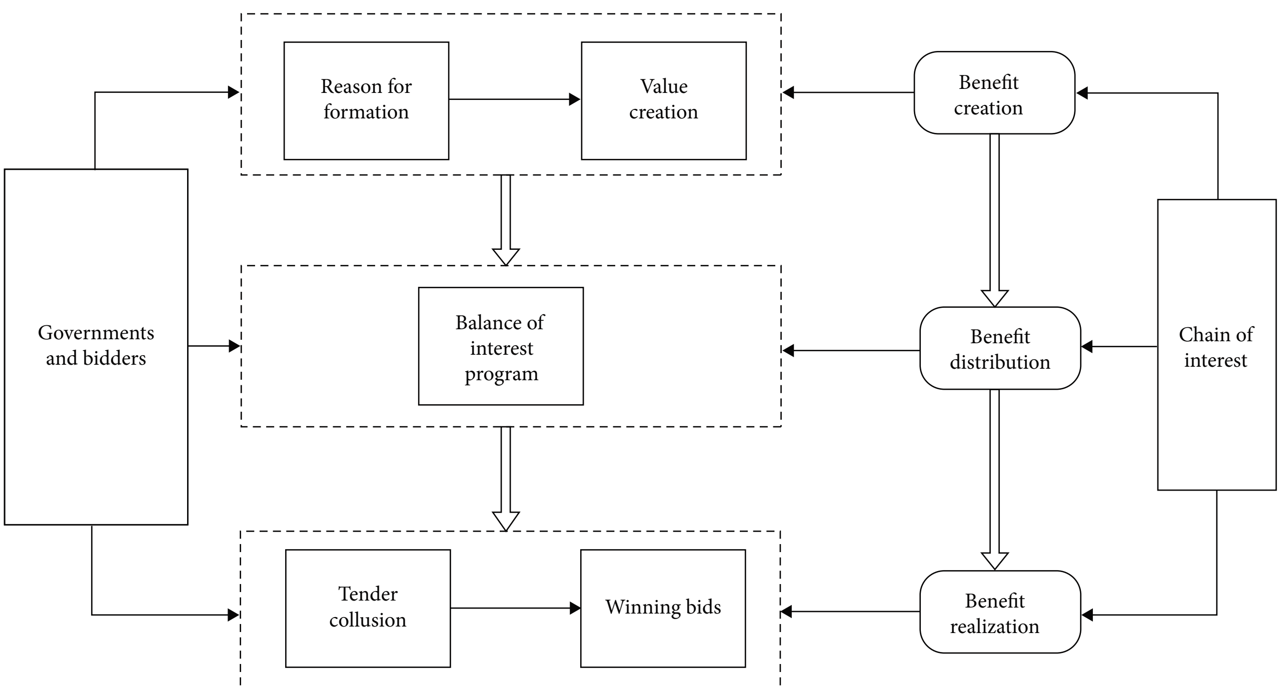

Figure 2: Basic conceptual framework of the grey chain of interests.

stage link in the grey interest chain. The "chain - stage - link - node" together constitute a complete grey interest chain, so in order to determine the formation process of the grey interest chain between the government and the bidders, we need to determine the specific nodes of each stage and link.

Based on the research and analysis of the three processes of benefit creation, benefit distribution, and benefit realization in the grey benefit chain between the government and the bidders, as well as reviewing relevant literature, and consulting relevant experts, this paper analyzed the relevant

Table 1: Key elements of the chain of interest.

Main links	Related content	Object of conduct	Research methodology
Benefit creation (A_1)	Project establishment (B_{11})	Government	Theoretical analysis
	Collusion intention of government (B_{12})	Government	Theoretical analysis
	Collusion Intention of bidders (B_{13})	Bidders	Theoretical analysis
	Collusion cost (B_{14})	Bidders	Theoretical analysis and expert consultation
	External risk sensitivity (B_{15})	Government and bidders	Theoretical analysis
	Core competence (B_{16})	Government	Theoretical analysis and expert consultation
	Resources integration (B_{17})	Government and bidders	Theoretical analysis
Benefit distribution (A_2)	Resources contribution (B_{21})	Government and bidders	Literature research
	Risk bearing (B_{22})	Government and bidders	Literature research
	Collusion satisfaction (B_{23})	Government and bidders	Literature research
	Negotiating ability (B_{24})	Government and bidders	Literature research
	Cooperative agreements (B_{25})	Government and bidders	Literature research
Benefit realization (A_3)	Tailor-made tender documents (B_{31})	Government	Questionnaires
	Pre-bid opening of bid documents (B_{32})	Government	Questionnaires
	Excluding others from bidding (B_{33})	Government	Questionnaires
	Standard settings (B_{34})	Government and bidders	Questionnaires and case studies
	Scoring weights are not set properly (B_{35})	Government	Questionnaires
	Enlisting experts of bid evaluation (B_{36})	Government	Questionnaires
	Scoring high for bidders (B_{37})	Government	Questionnaires and case studies
	Pre-qualification procedures are not public (B_{38})	Government	Questionnaires and case studies
	Modification of tender documents (B_{39})	Government	Questionnaires and case studies
	Set favorable vonditions for winning bids (B_{310})	Government	Case study
	Winning bids (B_{311})	Bidders	Theoretical analysis

nodes in each link and obtains a preselected set of benefit chain nodes, as shown in Table 1 below.

3.1.3. Key Node Identification. The node preselection set basically contains all the behaviors regarding the formation of the grey interest chain between government and bidders, which meets the requirement of comprehensiveness of the node content screening, but due to the large number of contents, there can also exist some behaviors that are repeated, at this time, the bias of the node content should be considered, and the more biased side should be selected, and the less biased side should be eliminated in time to avoid the repetition of its content as far as possible.

This paper uses a questionnaire to screen the 23 indicators in the nodal preselection set and finds that the Cronbach's α value of the questionnaire increases from 0.753 to 0.813 after excluding external risk sensitivity (B_{15}), negotiating ability (B_{24}), prebid opening of bid documents (B_{32}), standard settings (B_{34}), scoring weights are not set properly (B_{35}), prequalification procedures are not public (B_{38}), modification of tender documents (B_{39}), and set favorable conditions for winning bids (B_{310}). Therefore, these eight indicators are removed in this paper to determine the final node.

3.1.4. Grey Interest Chain Formation. The remaining nodes after screening are connected to form a grey chain of interests between government and bidders. The nodes are mainly divided into three categories: starting nodes, intermediate nodes, and ending nodes. In the construction process of government-invested projects, project creation or commissioning is the premise of all bidding activities, so it becomes the beginning node of the grey interest chain, and winning the bid is the final goal of the project, so it becomes the end node of the grey interest chain. The connecting line between the nodes indicates the logical relationship between the nodes, and there is a connection between Node A and Node B as long as there is a top–down relationship. Therefore, according to the bidding process, the time distribution of the nodes and the relationship of each node, the contents of each node are logically sorted out to obtain the formation process of the grey interest chain between the government and bidders, as shown in Figure 3.

3.2. Grey Interest Chain Control Model Construction. The current methods of network node importance analysis, such as degree centrality, betweenness centrality, and closeness centrality, can analyze the importance of nodes in the complex networks to different degrees or with different attributes, but the focus of the analysis is relatively single, which is bound to cause incomplete analysis of network nodes. Therefore, in this paper, the three indicators of degree centrality, betweenness centrality, and closeness centrality are evaluated

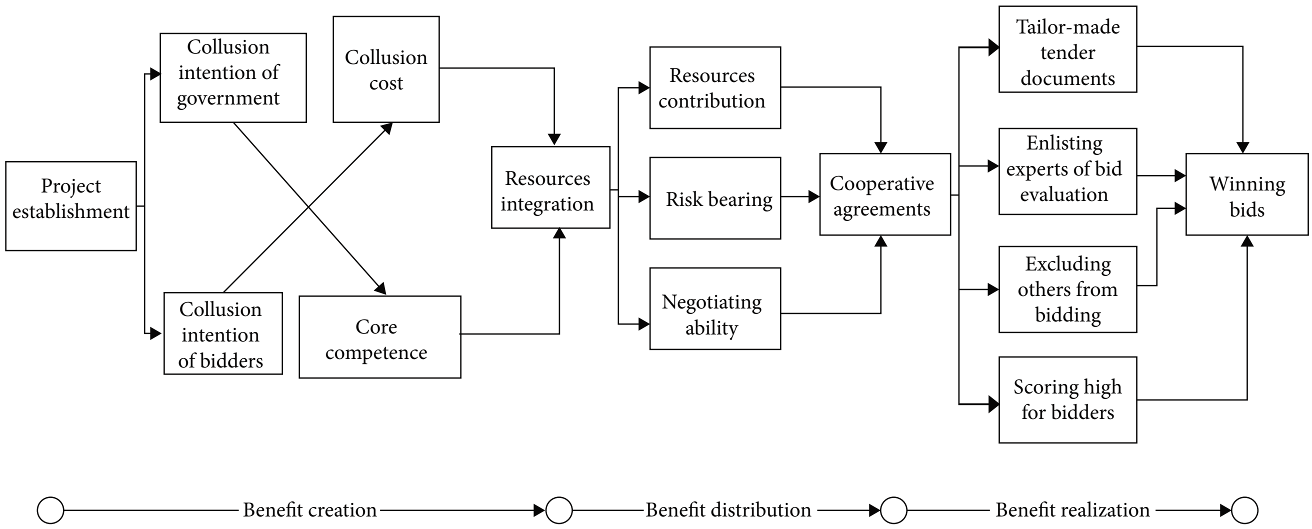

FIGURE 3: The process of forming a grey interest chain.

comprehensively, and the concept of cosine similarity is applied to construct a comprehensive analysis method of the importance of complex network nodes, so that the key nodes or key links of the grey interest chain between the government and bidders can be identified more scientifically.

3.2.1. Definition. Cosine similarity is used to measure the degree of similarity between vectors. The similarity of each node to the reference point is judged based on the cosine value between the position of each node and the reference point of the network. The method calculates the cosine of a vector node with respect to its optimal point to derive the relationship between each node and its optimal point, thus further identifying the key nodes in the network. The specific formula for calculating the cosine similarity is as follows:

$$\cos\theta = \frac{A\cdot B}{||A||\cdot||B||} = \frac{(a_1, a_2, a_3, \cdots, a_m)\cdot(b_1, b_2, b_3, \cdots, b_m)}{\sqrt{\sum_{i=1}^{m}(a_i)^2}\times\sqrt{\sum_{i=1}^{m}(b_i)^2}}. \tag{1}$$

3.2.2. Basic Parameters. Degree centrality is the ratio of the actual total number of edges connected to node i to the total number of possible edges connected to node i in the grey chain of interest, and it reflects the direct communication capability of the node, with a larger calculation indicating a higher communication capability. The formula for degree centrality is as follows, where K_i denotes the actual total number of edges connected to node i and N denotes the number of summary points.

$$DC_i = \frac{K_i}{(N-1)}. \tag{2}$$

Betweenness centrality is the ratio of the sum of the number of shortest paths through node i to the total number of shortest paths in the grey chain of interest, and it reflects the influence of the node in the network. The larger the calculated value, the greater the influence. The formula for medial centrality is as follows, where $g_{jk}(i)$ is the number of shortest paths between nodes j and k through node i and g_{jk} is the total number of all shortest paths between nodes j and k.

$$BC_i = \sum_{j\neq k}\frac{g_{jk}(i)}{g_{jk}}. \tag{3}$$

Closeness centrality is the ratio of the total number of nodes in the network to the sum of the shortest distances from a node to all the remaining nodes in the network. The larger the calculated value, the more important the degree of centrality of the network. The formula for proximity centrality is as follows, where d_{ij} is denoted as the shortest distance from node i to j. When two nodes are not connected, the maximum value of the shortest path in the network is taken.

$$CC_i = \frac{N}{\sum_{j=1}^{N} d_{ij}}. \tag{4}$$

The weights of the three indicators of degree centrality, betweenness centrality, and closeness centrality are calculated using the hierarchical analysis method, and the three indicators are determined by a two-by-two comparison method to obtain their judgment matrix and weights, as shown in Table 2.

3.2.3. Calculation Procedures. Suppose there are N nodes in a complex network, each with three evaluation indicators representing centrality, mediation centrality, and proximity centrality, and indicator j of node i is noted as X, thus forming a multiobjective decision matrix X.

$$X = \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix}. \tag{5}$$

As all three evaluation indicators are benefit-based indicators, the decision matrix of the indicators needs to be

Table 2: Determination of indicator weights.

Indicators	DC	BC	CC	Weights
DC	1			W_1
BC		1	2	W_2
CC			1	W_3

Table 3: Node rating criteria.

Node	Unimportant node	Average node	Important node	Critical node
Score	<0.7	0.7–0.8	0.8–0.9	>0.9

standardized for ease of calculation. The calculation formula is as follows, where $X_j^{\max} = \max\{X_{ij} | 1 \le i \le N\}$, resulting in the canonical decision matrix $R = (r_{ij})N \times m$.

$$r_{ij} = \frac{X_{ij}}{X_j^{\max}}. \tag{6}$$

Based on the statistical analysis of the questionnaire data, the indicator weights W_1, W_2, and W_3 of the three basic parameters of degree centrality, Mediation centrality and proximity centrality are calculated to obtain the weighting matrix Y.

$$Y = R \begin{bmatrix} W_1 \\ W_2 \\ W_3 \end{bmatrix}. \tag{7}$$

Select the ideal node $A(a_1, b_1, c_1)$, where a_1, b_1, c_1 are the maximum values of degree centrality, betweenness centrality, and closeness centrality, respectively. Then, the cosine similarity of each node to $A(a_1, b_1, c_1)$ was derived from Equation (1). Based on the calculation results, the nodes are classified into four levels of importance, critical node, important node, average node, and unimportant node, as shown in Table 3.

4. Case Study

In November 2013, during the bidding period for the construction general contracting project of a provincial motorway reexpansion project (Section 3), the project leader A repeatedly accepted cash from bidding enterprises and other issues. A used his position as a tenderer to accept cash, mobile phones and shopping cards from bidding enterprises on 12 occasions, with a total value of 599,100 yuan, during the bidding process for the highway renovation and expansion project, and facilitated the bidding process for bidding enterprises.

(1) A used the convenience of his position to allow his coconspirator bidder to win the tender and share some of the project benefits equally.

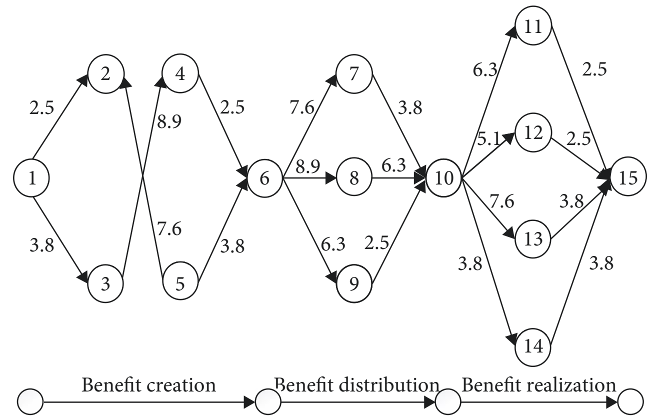

Figure 4: The network of grey interest chain formation.

(2) A used the convenience of his position to set special conditions on the tender documents such as bidding companies need to have a concrete tester to provide conspiracy bidders with the conditions for winning the tender.

(3) A used the convenience of his position to score high marks for the conspiracy bidder by greeting the tender evaluation committee, allowing him to obtain the winning bid.

(4) As a member of the tender evaluation committee, a scored high marks for the colluding bidders in the tender evaluation process.

The chain of interests in this collusion case was obtained by analyzing the main formation processes of the grey chain of interests in the previous section. This study invites the representative from the National Development and Reform Commission (e_1), influential and experienced practitioners in the field of tendering (the government e_2, the bidder e_3, the supervisor e_4, and the tender agent e_5), and the leading research scholar in the field of tendering (e_6). The ease of articulation between the nodes in the grey interest chain between the government and the bidders is then analyzed and the distance between the nodes is scored on a scale $U =$ {1, 2, 3, 4, 5}, which stands for (easy, fair, harder, difficult, and hard). By using the group assignment method, the weight values of the paths between the nodes can be obtained. To facilitate the calculation, the weights m are expanded by a factor of 100 and finally a network node diagram of the chain of interests between the government and the bidders is obtained, as shown in Figure 4.

The weights of degree centrality, betweenness centrality, and closeness centrality were calculated from the analysis of the questionnaire data as $W_1 = 0.163$, $W_2 = 0.540$, and $W_3 = 0.297$. Combine Equations (2)–(4) and the Matlab simulation to calculate the centrality index of each node of the government–bidder interest chain and construct the objective matrix of the relevant nodes of the government–bidder interest chain.

Table 4: Cosine similarity value of each node to the ideal point.

Nodes	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
Cosine value	0.537	0.831	0.813	0.896	0.894	0.991	0.907	0.917
Nodes	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	
Cosine value	0.907	0.903	0.716	0.735	0.735	0.658	0.59	

$$X = \begin{bmatrix} 0.143 & 0.000 & 0.058 \\ 0.143 & 2.911 & 0.065 \\ 0.143 & 4.151 & 0.065 \\ 0.143 & 23.287 & 0.099 \\ 0.143 & 19.786 & 0.090 \\ 0.357 & 63.030 & 0.143 \\ 0.143 & 41.603 & 0.289 \\ 0.143 & 39.346 & 0.224 \\ 0.143 & 42.207 & 0.340 \\ 0.500 & 152.273 & 0.515 \\ 0.143 & 23.652 & 0.079 \\ 0.143 & 23.363 & 0.085 \\ 0.143 & 22.620 & 0.073 \\ 0.143 & 21.472 & 0.092 \\ 0.143 & 2.000 & 0.087 \end{bmatrix}. \quad (8)$$

The matrix obtained after standardization and weighting is as follows:

$$Y = (Y_{ij}) = \begin{bmatrix} 0.053 & 0.000 & 0.025 \\ 0.053 & 0.006 & 0.028 \\ 0.053 & 0.009 & 0.028 \\ 0.053 & 0.048 & 0.043 \\ 0.053 & 0.041 & 0.039 \\ 0.132 & 0.131 & 0.062 \\ 0.053 & 0.086 & 0.125 \\ 0.053 & 0.082 & 0.097 \\ 0.053 & 0.088 & 0.147 \\ 0.184 & 0.316 & 0.224 \\ 0.053 & 0.049 & 0.034 \\ 0.053 & 0.048 & 0.037 \\ 0.053 & 0.047 & 0.032 \\ 0.053 & 0.045 & 0.040 \\ 0.053 & 0.005 & 0.038 \end{bmatrix}. \quad (9)$$

The maximum value of each column is derived from the weighting matrix, giving the ideal point as $A(0.184\ 0.316\ 0.224)$. Then, calculate the cosine similarity between the evaluation indicator vector of each node and the idealized node indicator vector A_i, and the cosine similarity results are shown in Table 4.

5. Discussion

The overall trend in the results of the cosine similarity calculations for each node shows that the rest of the cosine similarity values tend to increase upwards and then decrease downwards, so the importance of the government–bidder collusive interest chain should also gradually increase and then decrease.

In terms of the grade criteria for each node, resources integration (A_6), resources contribution (A_7), risk bearing (A_8), negotiating ability (A_9), and cooperative agreements (A_{10}) all have cosine similarity values greater than 0.9 to the ideal point and are critical nodes according to the node evaluation level. The cosine values of collusion intention of government (A_2), collusion intention of bidders (A_3), collusion cost (A_4), and core competence (A_5) lie above 0.8 and below 0.9 and are significant nodes. The three nodes of Tailor-made tender documents (A_{11}), enlisting experts of bid evaluation (A_{12}), and excluding others from bidding (A_{13}) have cosine similarity values above 0.7 and below 0.8 and are generally important nodes. The cosine similarity values of the three nodes of project establishment (A_1), scoring high for bidders (A_{14}), and winning bids (A_{15}) are all below 0.7, which are not significant nodes.

From the main formation links of the interest chain, A_6 and A_{10} are as the junction points between the interest allocation stage and other stages, and A_7, A_8, and A_9 are exactly in the interest allocation stage, indicating that the nodes in the interest allocation stage have the greatest influence in the formation of the grey interest chain between the government and the bidders. In addition to the nodes within the benefit distribution link, A_2, A_3, A_4, and A_5 are in the benefit creation stage of the grey benefit chain and have a more important influence on the formation of the grey benefit chain of the government and the bidders. A_{11}, A_{12}, and A_{13} belong to the content of benefit realization, and these nodes have an average degree of influence on the formation process of the government and the bidders. The remaining nodes A_1, A_{14}, and A_{15} have less influence on the formation of grey interest chain.

Based on the previous analysis of the formation process and key control points of the grey interest chain between the government and bidders, the integration of resources between the government and bidders in the benefit creation stage is bound to hinder the effective allocation of other resources and bring losses to social welfare, at this time, the principle of preventive control is adopted for the important nodes in the benefit creation stage, which can be achieved through innovative bidding document review methods, incorporating the preparation of bidding documents into the work appraisal system, entrusting consulting units or third parties to prepare bidding documents, and other specific measures to establish a grey resource integration cracking mechanism. In the benefit distribution stage, the government and bidders try to gain more benefits, and while gaining benefits, they are bound to cause certain risks to the project quality of their projects. At this time, the key nodes in the benefit distribution stage are comprehensively controlled, and the amount of economic penalties for the government and bidders can be appropriately increased, the system of equal responsibility for enterprises and project leaders is implemented, and the regulations of collusion penalties for bidders are appropriately subdivided to strictly supervise the government and bidders' behavior and establish a perfect reputation mechanism on the basis of ensuring open and transparent information. In the benefit realization stage, the government and bidders adopt various collusive behaviors, which violate the fair, just and open principles of bidding. Process control should be carried out for the general and unimportant nodes of the benefit realization stage. The bidding system should be improved and the postaward audit should be strengthened to make the realization of grey benefits more difficult.

6. Conclusion and Research Limitations

6.1. Conclusion. In related studies in recent years, Ma et al. [27] finds that collusion in the bidding process for Chinese government investment projects can be addressed by reducing the atmosphere of social collusion, playing a market-led role, and strengthening supervision and control. According to Yu et al. [28] research, there is a "self-reinforcing" phenomenon of bid collusion, and it is recommended to pay attention to the early management of collusion in the industry. Jie and Hong-yuan [29] believe that strong regulatory mechanisms, sound contractual governance, and a strong belief in trust can effectively avoid collusive behavior facilitated by moral hazard. It was found that each of the three types of collusion —interventional, opportunistic, and cooperative—has its own characteristics and patterns, and that the variables affecting the types of collusion have complex relationships and influence each other [15]. In related studies in recent years, Xiaoting [30] proposed governance countermeasures based on three elements: colluding actors, resources, and events. The comprehensive evaluation model of the tendency of vertical collusion established by the study has a certain reference value for the regulation of the bidding market in countries such as China [20].This paper is devoted to the study of vertical collusion in the government investment project bidding, focusing on the formation process of grey interest chain between government and bidders, identification of control nodes, and design of the control measures, which on the one hand enriches the theory of collusion research at this stage and transforms the collusion problem from qualitative analysis to quantitative analysis, and makes the abstract chain into a concrete chain. On the other hand, it strengthens the practicality and helps to provide a breakthrough point for solving the vertical collusion problem, reduce the occurrence of vertical collusion in bidding, promote the specification of bidding market, and improve the overall level of construction industry. The main research findings are as follows:

(1) Through literature research, the concept of grey interest chain is innovatively used in the study of bidding collusion in government investment projects, and the basic conceptual framework of grey interest chain in bidding is constructed from three stages of benefit creation, benefit distribution, and benefit realization, which provides a new method for the related research of bidding collusion.

(2) The SPSS 19.0 confidence method was used to determine the content of the three stages of the interest chain consisting of 15 nodes, and based on the relationship between the bidding process and each node, the logical relationship of each node was analyzed and classified according to its importance in a hierarchical manner to determine the formation process of the grey interest chain between the government and bidders from an overall perspective.

(3) The node control methods are analyzed and integrated, and three methods of degree centrality, betweenness centrality, and closeness centrality are used as indicators to integrate to obtain a grey interest chain control model of the government and bidders to reduce the one-sidedness of the node identification results of a single method.

(4) Through the node identification results of specific cases, we propose targeted measures to control the grey interest chain between the government and bidders, thus blocking the formation of the grey interest chain between the government and bidders, reducing the problem of vertical collusion in bidding, and providing reference for the other cases of collusion in bidding in the real situations.

6.2. Limitations. Due to the complexity of studying the grey interest chain between the government and bidders, there are many limitations and shortcomings in this paper. First, the key interest chain is mainly based on the stakeholder theory from three perspectives, such as benefit creation, benefit distribution, and benefit realization, which may be analyzed differently, based on the different perspectives or theories, and may eventually lead to different analysis results, so it is necessary to consider this formation process more comprehensively. Second, the nodal distance is based on the group empowerment method, which takes into account the different preferences of experts to a certain extent, and the number of experts is limited, so if enough experts are selected for the survey, the results may be more accurate. At the same time, if the data are processed with the help of computer technology to develop a relevant measurement system, it is possible to quickly process the data and flexibly supplement or refine the indicators, which can greatly improve the efficiency and quality of the measurement.

Data Availability

All data generated or analyzed during this study are personal and can only be provided after the project has been approved.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] C. Jie and H. Yunfei, "Research on identification of multi-stakeholder collusion in engineering project bidding," *Journal of Railway Science and Engineering*, vol. 17, pp. 784–790, 2020.

[2] D. U. Xinghua, "Game analysis of collusive bidding in public procurement," *Journal of Soochow University (Philosophy & Social Science Edition)*, vol. 38, pp. 97–103, 2017.

[3] H. Shi, X. Li, and H. Xu, "Game analysis on collusion tender in the construction projects bidding," *Applied Mechanics and Materials*, vol. 357–360, pp. 2414–2419, 2013.

[4] R. M. Abrantes-Metz and P. Bajari, "Screens for conspiracies and their multiple applications," *Competition Policy International*, vol. 8, no. 1, pp. 177–193, 2012.

[5] M. K. Kadalbajoo and V. Gupta, "A brief survey on numerical methods for solving singularly perturbed problems," *Applied Mathematics and Computation*, vol. 217, no. 8, pp. 3641–3716, 2010.

[6] J. Miklós-Thal, "Optimal collusion under cost asymmetry," *Economic Theory*, vol. 46, no. 1, pp. 99–125, 2011.

[7] R. Burguet and M. K. Perry, "Bribery and favoritism by auctioneers in sealed-bid auctions," *The B.E. Journal of Theoretical Economics*, vol. 7, no. 1, Article ID 0000102202193517041219, 2007.

[8] C. Z. Zheng, "Bidding collusion without passive updating," *Journal of Mathematical Economics*, vol. 85, pp. 70–77, 2019.

[9] X. Wang, D. Arditi, and K. Ye, "Coupling effects of economic, industrial, and geographical factors on collusive bidding decisions," *Journal of Construction Engineering and Management*, vol. 148, no. 7, 2022.

[10] I. K. Lee and K. Hahn, "Bid-rigging in auctions for Korean public-works contracts and potential damage," *Review of Industrial Organization*, vol. 21, pp. 73–88, 2002.

[11] R. Signor, P. E. D. Love, A. T. N. Belarmino, and O. Alfred Olatunji, "Detection of collusive tenders in infrastructure projects: learning from operation car wash," *Journal of Construction Engineering and Management*, vol. 146, no. 1, 2020.

[12] R. Signor, P. E. D. Love, A. Oliveira Jr., A. O. Lopes, and P. S. Oliveira Jr., "Public infrastructure procurement: detecting collusion in capped first-priced auctions," *Journal of Infrastructure Systems*, vol. 26, no. 2, 2020.

[13] A. M. Kwasnica and K. Sherstyuk, "Multiunit auctions," *Journal of Economic Surveys*, vol. 27, no. 3, pp. 461–490, 2013.

[14] M. Pesendorfer, "A study of collusion in first-price auctions," *Review of Economic Studies*, vol. 67, no. 3, pp. 381–411, 2000.

[15] S. Nie, Y. Chen, J. Li, W. Zhu, and C. Ma, "Analysis on the types and characteristics of collusion behavior of government investment project tenderees," *Complexity*, vol. 2022, Article ID 5159393, 13 pages, 2022.

[16] P. Bowen, R. Pearl, and A. Akintoye, "Professional ethics in the South African construction industry," *Building Research & Information*, vol. 35, no. 2, pp. 189–205, 2007.

[17] C. Yun, W. Can-Can, and Z. Wen-Xi, "The method of calculating the collusion intensity of government project tenderers and bidders based on evidence reasoning," *Journal of Changsha University of Science and Technology (Natural Science)*, vol. 15, no. 1, pp. 57–62, 2018.

[18] M. Aoyagi, "Bid rotation and collusion in repeated auctions," *Journal of Economic Theory*, vol. 112, no. 1, pp. 79–105, 2003.

[19] M. Huber and D. Imhof, "Machine learning with screens for detecting bid-rigging cartels," *International Journal of Industrial Organization*, vol. 65, pp. 277–301, 2019.

[20] W. Zhu, K. Cheng, Y. Guo, and Y. Chen, "Comprehensive evaluation of the tendency of vertical collusion in construction bidding based on deep neural network," *Computational Intelligence and Neuroscience*, vol. 2022, Article ID 2897672, 13 pages, 2022.

[21] M. J. G. Rodríguez, V. Rodríguez-Montequín, P. Ballesteros-Pérez, P. E. D. Love, and R. Signor, "Collusion detection in public procurement auctions with machine learning algorithms," *Automation in Construction*, vol. 133, Article ID 104047, 2022.

[22] C. Ma, Y. Chen, and Z. Lei, "Evaluation of the effectiveness of collusion control policy implementation by BP neural network based on annealing algorithm optimization," *Mathematical Problems in Engineering*, vol. 2022, Article ID 9238838, 8 pages, 2022.

[23] M. Sohail and S. Cavill, "Accountability to prevent corruption in construction projects," *Journal of Construction Engineering and Management*, vol. 134, no. 9, pp. 729–738, 2008.

[24] G. Van Den Heuvel, "The parliamentary enquiry on fraud in the Dutch construction industry collusion as concept between corruption and state–corporate crime," *Crime, Law and Social Change*, vol. 44, no. 2, pp. 133–151, 2005.

[25] E. Elahi, Z. Khalid, M. Z. Tauni, H. Zhang, and X. Lirong, "Extreme weather events risk to crop-production and the adaptation of innovative management strategies to mitigate the risk: a retrospective survey of rural Punjab, Pakistan," *Technovation*, vol. 117, p. 102255, 2022.

[26] Z. He, D. Huang, C. Zhang, and J. Fang, "Toward a stakeholder perspective on social stability risk of large hydraulic engineering projects in China: a social network analysis," *Sustainability*, vol. 10, no. 4, Article ID 1223, 2018.

[27] C. Ma, Y. Chen, W. Zhu, and L. Ou, "How to effectively control vertical collusion in bidding for government investment projects-based on FSQCA method," *PLOS ONE*, vol. 17, no. 9, Article ID e0274002, 2022.

[28] Z. Yu, L. Wei, and L. Qi, "A study on the reverse evolution of industrial upgrading in the bid collusion environment," *Science and Technology for Development*, vol. 17, no. 2, pp. 367–374, 2021.

[29] C. Jie and F. Hong-yuan, "Research on factors influencing the tendency of collusive behavior of multi-interest subjects in engineering project bidding," *Journal of Xiangtan University (Philosophy and Social Sciences)*, vol. 44, no. 3, pp. 43–51, 2020.

[30] Ye Xiaoting, "Analysis of collusive behavior of engineering bidding under network characteristics and research on countermeasures," *Urban Housing*, vol. 28, no. 10, pp. 254–256, 2021.