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Research on the Causal Chain of Vertical Collusion in Bidding for Government Investment Projects

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Abstract

Effective control of collusive behavior in the government bidding process is a prerequisite for promoting the high-quality development of social economy, consolidating the results of the anti-corruption struggle and the smooth operation of the project. Based on risk theory and Bayesian networks, this paper uses GeNIE 4.0 software to construct a Bayesian network structure model to analyze the causal chain of vertical collusion in government project tendering processes. The study found three key causal chain paths: ① external supervision subject to collusion gains, external environment, competitive pressure, and lack of compliance awareness of the formation of "external supervision subject → response subject → vertical collusion" regulatory failure of vertical collusion path; ② rights subject to collusion gains, the external environment, and the lack of publicity of policies and regulations. External supervision is influenced by collusion gains, the external environment, competitive pressure, and compliance awareness of the formation of the "rights subject → external supervision subject → response subject → vertical collusion" internal and external collusion path; the rights of the subject, affected by the collusion gains, the external environment, and the lack of publicity of policies and regulations, form a collusion path of uncontrolled rights. It is also found that, at the subject level, the subject of rights and the subject of external supervision are in a key position in the control process; at the factor level, the control of collusion proceeds, the publicity of policies and regulations, and the external environment can significantly enhance the control effect of vertical collusion and provide a precise focus for the collusion chain to break the chain.

Keywords: vertical collusion; government investment projects; bidding; causal chain; Bayesian network structure model; GeNIE

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1. Introduction

As China's reform has entered the deep-water zone, the question of how to promote high-quality economic and social development through deeper reforms and higher levels of openness has become a crucial issue. Government departments at all levels in China increasingly recognize that accelerating the implementation of major projects plays a vital role in advancing supply-side structural reform and stabilizing economic growth. However, the 14th Five-Year Plan meeting pointed out that "the overall level of China's infrastructure remains insufficient, and government investment in related fields should be increased". This indicates that government investment will play a significant role in the construction of major projects.

Bidding is an effective method of resource acquisition and allocation formed through long-term socio-economic activities. In China's government-funded projects, the bidding process is predominantly used to determine project contractors. The bidding and procurement system for government-funded projects was originally designed to prevent corruption. However, in practice, vertical collusion remains a persistent issue. Therefore, exploring how to effectively control vertical collusion is of great importance.

As a social problem, "collusion" exists in all stages of economic and social development [1–3]. At present, the research on collusion is mainly concentrated in the field of public management [4,5]. Practice has proved that the project with collusion behavior is often accompanied by management chaos, serious safety hazards, and quality problems, threatening the public security of society [6–8].

Laffont et al. studied collusive behavior in industrial organizations and identified the classic collusion research paradigm, studied the causes, factors, and prevention of behavior, and pointed out that the collusion paradigm generally consists of three layers: the principal, the regulator, and the agent (P-S-A) [9]. Guo Jianming et al. pointed out that vertical collusion can lead to the emergence of "public bribery" corruption behavior and produce adverse social impact and large economic losses [10]. Zhu Wenxi et al. studied the conditions of bidding collusion space behavioral factors, pointing out that the competitive pressure of the market and the bidding execution process can lead to bidding collusion behavior [11]. Yang et al. argued that collusive behavior can bring losses to project interests [12].

Engineering project bidding is a high incidence of collusion. Scheepbouwer et al. pointed out through research that collusion will exist for a long time in the bidding process of engineering projects [13]. The bidding process of an engineering project includes bidders, bidding agencies, bid evaluation experts, supervisory bodies, and other types of participating subjects. According to the status of the conspirators in the bidding process of engineering projects, the conspiracy behavior can be divided into vertical conspiracy and horizontal conspiracy [14]. Vertical conspiracy refers to collusion behavior between conspirators in which there is a hierarchical difference between the relationship, such as direct or indirect instruction relationships, mainly occurring between the bidder, supervisory body, and the bidding agency within the vertical hierarchy. Its unique characteristics are mainly reflected in the fact that collusion occurs between vertical entities at different levels, which may use hierarchical power differences to cover up irregular operations. At the same time, vertical collusion involves multiple links such as decision-making, execution, and supervision, which not only directly damages the safety of public funds and engineering quality, but also causes systemic erosion of the bidding market.

The control path for bidding collusion is mainly divided into two kinds of preventive and punitive [15,16]. Zhu et al. pointed out that bidding collusion has been a deep-rooted problem in the construction market, and increasing the certainty and severity of the punishment can improve the deterrent effect on the collusive behavior to achieve the control of the collusive behavior, but there is a marginal diminishing effect of the deterrence and the deterrent effect cannot be achieved as a complete alternative [16]. Fang et al. point out that an effective and transparent bidding system can regulate the behavior of bidders by rewarding the most qualified bidders and achieve control of collusion [17]. The rationale for using punitive methods to reduce the incidence of collusive behavior is to send a strong signal of regulation to market participants by detecting and punishing existing bid manipulators [18,19]. Feess et al. point out that increased penalties are often considered the preferred choice to enhance deterrence of misconduct such as corruption and collusion; however, increasing the magnitude of penalties may be counterproductive when potential violators anticipate that the probability of penalties will decrease [20]. Some researchers

have applied machine learning algorithms to detect collusion and bidding manipulation. García attempted to identify collusive behaviors through data learning [21]. Regarding collusive behavior, Signor et al. proposed and discussed a procedure for constructing robust reference scenarios to detect bid manipulation in first-price auctions for infrastructure through their research, providing a means for collusion control [22].

In summary, existing research on bidding collusion is mostly based on deterministic research issues, with less attention to the formation path of vertical collusion and corresponding control measures. Therefore, this paper combines risk theory and Bayesian networks to explore the main formation path of vertical collusion and construct targeted control measures.

The main research questions of this paper include the following:

Q1. Which entities and factors play a key role in vertical collusion in government-invested engineering projects?

Q2. How do entities and factors interact in formation of vertical collusion chains?

2. Materials and Methods

2.1. Identification and Screening of Key Subjects and Factors in the Causal Chain

2.1.1. Identification of Key Subjects and Factors in the Causal Chain

By combing the existing literature and interview, Preliminary Master Determination and 25 key factors in seven categories such as external environment, competitive pressure, and collusive gain were identified, preliminary master determination, key impact factor and interview questions as shown in Tables 1–3.

Table 1. Preliminary Master Determination.

Primary Indicator	Secondary Indicator	Indicator Definition	Indicator Source
Right Holder (Z1)	Tendering Party	Responsible persons of the tendering enterprise group (legal representative, actual controller, and branch GM) Mid-level department heads and regular employees Government officials (including relatives)	Wang [23], Chen [24], Ma [25], Zhou [26], and interview
External Supervision Entity (Z2)	Regulatory Body	External supervisory institutions such as regulatory authorities	Wang [23], Wang [27], and interview
Internal Supervision Entity (Z3)	Other Entities	Bidding participants who actively report collusion activities	Chen [24], Ma [25], and interview
Responding Entity (Z4)	Vertically Colluding Bidding Participants	Responsible persons of the bidding enterprise group (legal representative, actual controller, and branch GM) External solicitors	Wang [27], Zhou [26], and interview

Table 2. Identification of key impact factors.

Primary Indicator	Secondary Indicator	Indicator Source
External Environment (A1)	Selective Law Enforcement (A11) Close Personal Relationships (A12) Following Superior's Instructions (A13) Lack of Fund Flow Supervision (A14)	Wang [23,27], Song [28] and interview
Competitive Pressure (A2)	Unable to Win Projects Without Collusion (A21) Unable to Conduct Follow-up Work Without Collusion (A22) Market Competition Level (A23)	Kapoguzov [29], Chen [24] and interview
Control Systems (A3)	Incomplete Systems (A51) Special Rectification Campaigns (A52) Perfunctory Bidding Process (A53) Inadequate Supervision (A54)	Ma [25] and Wang [27] and interview

Table 2. *Cont.*

Primary Indicator	Secondary Indicator	Indicator Source
Policy Promotion (A4)	Insufficient Education (A61) Lack of Illegal Act Awareness (A62) Initiative to Protect Bidding Market (A63)	Ma [25] and interview
Collusion Benefits (A5)	Personal Interests (A31) High Project Profits (A32) Interests of Relatives and Friends (A33) Collusion Costs (A34)	Shanglyu [30] and interview
Enterprise Development (A6)	Obtaining Excess Returns (A41) Securing Future Development (A42) Financial Security (A43) Gaining Recognition (A44)	Zhang [31], Zhang [32] and interview
Compliance Awareness (A7)	Risk Awareness (A71) Social Climate (A72) Secret Collusion Process/Benefit Transfer Methods (A73)	Ma [25,33] and interview

Table 3. Interview questions.

Interview Questions
1. Who do you think are the main participants in vertical collusion?
2. Under what circumstances do you think bidders may choose to participate in vertical collusion?
3. What do you think causes the government/tenderer to accept collusion requests?
4. What do you think causes the existence of collusion among bidders/affects collusion among bidders?
5. What kind of external environment do you think would lead to an increase in collusion?

2.1.2. Screening of Key Subjects and Factors in the Causal Chain

In this paper, the identified influencing factors are used as the nodes for analyzing the causal role relationship of the vertical collusion chain of bidding for government investment projects, in order to ensure the validity of the questionnaire and to facilitate the data collection of a large-scale sample. Before the official questionnaire was distributed, one government staff, one scholar, and two bidding practitioners were interviewed, and the questionnaire was adjusted based on the interviewed group's perceptions of the research questions, the clarity of the questionnaire's questionnaire descriptions, etc. The questionnaire items were modified to form a questionnaire that was easy to comprehend and clear in its presentation, and the pre-testing of the questionnaire was further carried out.

Before the formal collection of questionnaires, the proposed research group explained the purpose of this research and the content of the study, assured participants of anonymity and non-commercial use, and gained their support and assistance for the formal research process. At the same time, in order to expand the sample size to meet the needs of the analysis, a professional data collector was hired through outsourcing to collect the relevant questionnaires. We distributed and collected a total of 126 questionnaires, with a sample validity rate of 92.86% (117 questionnaires). Table 4 shows the basic information of the research group.

Table 4. Basic information of research groups.

Item	Category	Sample Size	Proportion
Gender	Male	73	62.4%
	Female	44	37.6%

Table 4. *Cont.*

Item	Category	Sample Size	Proportion
Education	College/Associate degree or below	40	34.2%
	Bachelor's degree	61	52.1%
	Master's degree or above	16	13.7%
Work Experience	Less than 5 years	39	33.3%
	5–15 years	37	31.6%
	15–25 years	24	20.5%
	More than 25 years	17	14.5%

Reliability tests on the questionnaire were further conducted using SPSS 27. The overall reliability analysis results of the questionnaire are shown in Tables 5 and 6.

Table 5. Overall reliability analysis of the probability of factors influencing the vertical collusion chain of bidding in government investment projects.

Number of Valid Samples	Cronbach's α	McDonald's ω
117	0.890	0.879

Table 6. Overall reliability analysis of the influence degree of factors on the vertical collusion chain of bidding in government investment projects.

Number of Valid Samples	Cronbach's α	McDonald's ω
117	0.891	0.878

From Tables 5 and 6, it can be found that the overall Cronbach's α value of the collusion chain probability of influencing factors' role from the questionnaire is 0.890, and the overall Cronbach's α value of the degree of influence of factors is 0.891. This shows that the evaluation indexes as a whole have a high degree of reliability and can be analyzed in depth. Existing studies point out that, for multidimensional scales, McDonald's ω reliability can better reflect the overall reliability of the document compared to the Cronbach's α value. Therefore, the McDonald's ω reliability was further calculated, yielding values of 0.879 and 0.878, both of which are greater than 0.8. The overall reliability of the document is better and can be further analyzed. After the overall reliability of the document was verified, the reliability of each dimension question item was further tested.

From the analysis of Tables 7 and 8, it can be seen that the CITC values of all items are greater than 0.4, indicating that there is a good correlation between the analyzed items and also that the level of reliability is good. In addition, the Cronbach's α values of the indicators are greater than 0.7, and the deletion of any item fails to significantly increase the Cronbach's α value, indicating that the items have good reliability. The Cronbach's α values of the indicators are all greater than 0.7, and the deletion of any of the items does not significantly increase the Cronbach's α value, indicating that the items have good internal consistency. Therefore, all the items are retained.

Table 7. Table of Reliability Analysis on the Probability of Causal Effects in the Vertical Collusion Chain of Government-Invested Project Bidding and Tenderin.

Item	Corrected Item Total Correlation (CITC)	Cronbach's α Value After Deletion of the Item	Cronbach's α
A11	0.707	0.773	0.835
A12	0.649	0.799	
A13	0.671	0.789	
A14	0.637	0.804	
A21	0.656	0.850	0.850
A22	0.715	0.796	
A23	0.793	0.719	
A31	0.647	0.829	0.851
A32	0.695	0.809	
A33	0.762	0.779	
A34	0.664	0.822	
A41	0.768	0.801	0.870
A42	0.728	0.842	
A43	0.763	0.809	
A51	0.732	0.801	0.855
A52	0.723	0.805	
A53	0.612	0.850	
A54	0.726	0.804	
A61	0.622	0.735	0.795
A62	0.541	0.774	
A63	0.626	0.733	
A64	0.633	0.729	
A71	0.654	0.805	0.832
A72	0.694	0.767	
A73	0.732	0.727	

Table 8. Confidence analysis of the degree of influence of factors on the vertical collusion chain in bidding for government investment projects.

Item	Corrected Item Total Correlation (CITC)	Cronbach's α Value After Deletion of the Item	Cronbach's α
A11	0.751	0.806	0.861
A12	0.728	0.815	
A13	0.692	0.831	
A14	0.669	0.839	
A21	0.713	0.785	0.846
A22	0.689	0.808	
A23	0.738	0.763	
A31	0.743	0.798	0.856
A32	0.695	0.819	
A33	0.707	0.814	
A34	0.657	0.835	
A41	0.676	0.710	0.806
A42	0.650	0.738	
A43	0.634	0.755	
A51	0.768	0.816	0.870
A52	0.685	0.849	
A53	0.698	0.844	
A54	0.744	0.825	

Table 8. *Cont.*

Item	Corrected Item Total Correlation (CITC)	Cronbach's α Value After Deletion of the Item	Cronbach's α
A61	0.651	0.784	0.827
A62	0.663	0.778	
A63	0.669	0.775	
A64	0.631	0.792	
A71	0.593	0.687	0.764
A72	0.589	0.690	
A73	0.606	0.672	

In this section, exploratory factor analysis was taken to measure the validity of the variables, which was suitable for factor analysis through Kaiser–Meyer–Olkin values greater than 0.7. Tables 9 and 10 show principal component analysis. A total of seven factors were extracted, the cumulative explanatory rate is greater than 70%, and the common degree is greater than 0.4; the factor dimensions are consistent with expectations, and there is no need to make further adjustments to the questionnaire.

Table 9. Table of Validity Analysis on the Probability of Causal Effects in the Vertical Collusion Chain of Government-Invested Project Bidding and Tendering.

Item	Factor Loading							Communality
	1	2	3	4	5	6	7	
A11			0.810					0.716
A12			0.780					0.681
A13			0.826					0.739
A14			0.787					0.678
A21						0.824		0.710
A22						0.832		0.777
A23						0.877		0.833
A31		0.771						0.648
A32		0.801						0.718
A33		0.823						0.803
A34		0.813						0.720
A41				0.892				0.828
A42				0.834				0.760
A43				0.875				0.817
A44	0.779							0.739
A51	0.847							0.767
A52	0.727							0.631
A53	0.835							0.757
A54					0.700			0.627
A61					0.753			0.660
A62					0.655			0.647
A63					0.662			0.623
A71							0.729	0.722
A72							0.820	0.802
A73							0.713	0.760
Total Variance Explained								
Eigenvalue	7.091	2.554	2.188	1.979	1.886	1.343	1.120	
Cumulative Variance Explained (%)	28.365	38.582	47.333	55.251	62.797	68.170	72.650	
KMO				0.813				
Bartlett's Test Statistic				1482.444				
p				<0.001				

Table 10. Table of Validity Analysis of the Influence Degree of Factors on the Vertical Collusion Chain in Bidding for Government Investment Projects.

Item	Factor Loading							Communality
	1	2	3	4	5	6	7	
A11		0.859						0.756
A12		0.842						0.740
A13		0.841						0.717
A14		0.781						0.680
A21					0.850			0.786
A22					0.814			0.728
A23					0.836			0.799
A31			0.803					0.775
A32			0.783					0.704
A33			0.838					0.756
A34			0.743					0.662
A41						0.786		0.733
A42						0.833		0.752
A43						0.821		0.747
A44	0.847							0.780
A51	0.792							0.696
A52	0.798							0.758
A53	0.788							0.777
A54				0.636				0.647
A61				0.714				0.649
A62				0.780				0.786
A63				0.782				0.692
A71							0.773	0.681
A72							0.742	0.708
A73							0.650	0.684
Total Variance Explained								
Eigenvalue	7.199	2.809	2.230	1.735	1.655	1.376	1.188	
Cumulative Variance Explained (%)	28.795	40.031	48.951	55.892	62.512	68.016	72.769	
KMO				0.799				
Bartlett's Test Statistic				1521.866				
p				<0.001				

It can be seen that the designed questionnaire items can better reflect the content of the study, and the dimensions are reasonably divided to allow for formal questionnaire collection and data analysis.

2.2. Bayesian Networks

A Bayesian network, through the analysis of a priori probability and a posteriori probability, can be adapted to the uncertainty of the relationship between the reasoning and analysis of the research. By applying reverse inference and sensitivity analysis within the Bayesian network, it can realize the analysis of the causal relationship in the vertical collusion chain. GeNIE4.0 was chosen to analyze the causal chain of vertical collusion in bidding for government investment projects.

Before constructing the Bayesian network model and parameter learning, the data obtained from the questionnaire survey need to be preprocessed. Drawing on the field of risk management and the processing in the existing literature, the two-dimensional matrix, composed of the probability of the possible role of the influencing factors and the severity of the consequences caused by the two-dimensional matrix, is transformed into a one-dimensional matrix. This allows classification into three risk categories: low, medium,

and high risk, labeled as Low, Middle, and High, respectively. The schematic diagram of the matrix is shown in Figure 1.

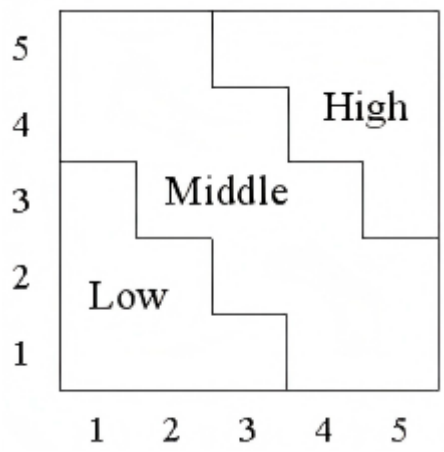


Figure 1. Data processing matrix.

Taking into account the characteristics of the research content and data collection, this project constructs a Bayesian network of causal relationships in the vertical collusion chain of bidding for government investment projects through previous experience and adjusts the network results according to the results of expert interviews. The network structure is shown in Figure 2.

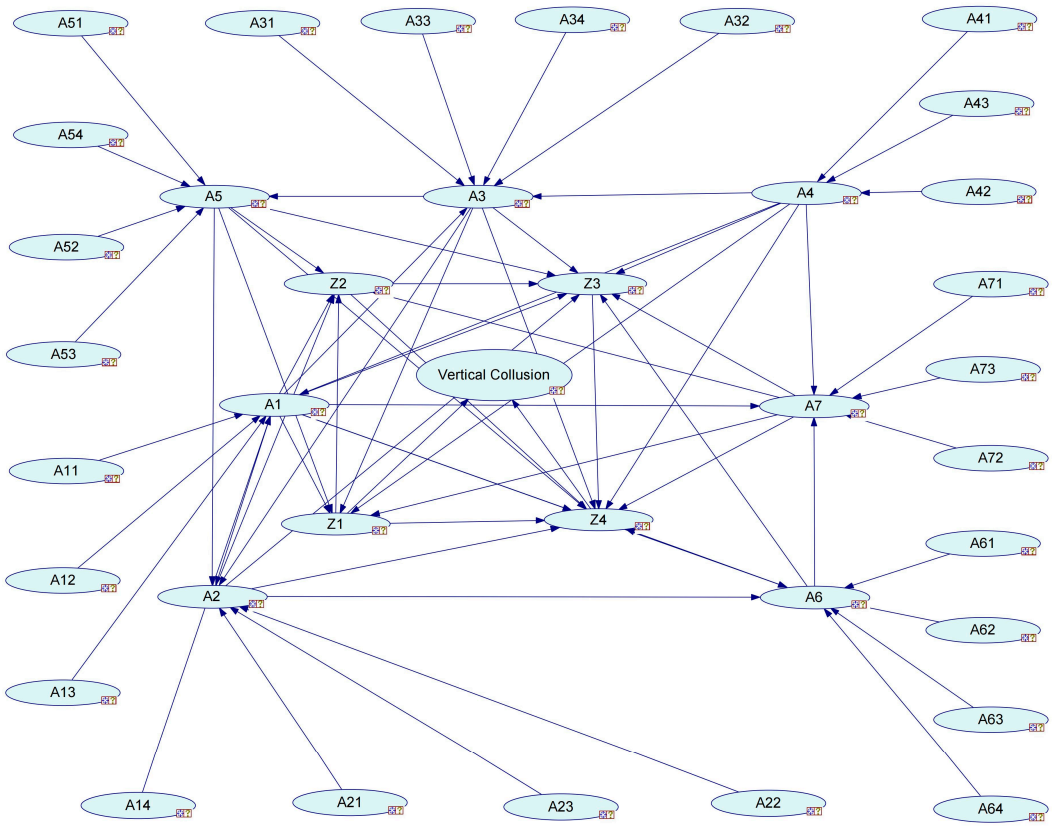


Figure 2. Network structure diagram.

In Figure 2, we have preliminarily constructed the possible relationships between influencing factors and subjects. Among them, A11–A73 are the influencing factors, and Z1–Z4 are subjects (the corresponding relationships are shown in Tables 1 and 2).

2.3. Model Construction

After determining the final questions and questionnaires, the questionnaires were formally distributed. The formal questionnaire adopts a five-level Likert scale. Formal research questionnaire collection began in September 2023, taking a combination of online and offline way. Questionnaires that were completed too quickly or had duplicate IP addresses and other invalid questionnaires were removed, leaving 470 valid questionnaires.

The basic situation of the researched group is shown in Table 11. This group demonstrates high representativeness and professionalism in terms of gender ratio, educational background, and work experience. The gender distribution of the sample aligns closely with the industry workforce composition, ensuring the data's generalizability; 73.2% of respondents hold a bachelor's degree or higher, and over 70% have more than five years of work experience, indicating a solid theoretical foundation and extensive practical experience, enabling them to provide high-quality feedback. Additionally, by rigorously screening out invalid questionnaires (such as those with insufficient completion time or duplicate IP addresses) and combining data collection through multiple online and offline channels, the reliability and comprehensiveness of the data were further ensured. Therefore, these 470 valid questionnaires provide scientific support for the research conclusions, enhancing their applicability and persuasiveness in the field of government investment bidding.

Table 11. Basic information on research groups.

Project	Category	Sample Size	Proportion
Gender	Male	283	60.21%
	Female	187	39.79%
Academic qualifications	College and below	126	26.80%
	Undergraduate	230	48.94%
	Graduate student and above	114	24.26%
Years of working experience	Less than 5 years	129	27.45%
	5−15 years	141	30.00%
	15−25 years	130	27.66%
	More than 25 years	70	14.89%

3. Results

3.1. Parameter Learning

On the basis of the constructed Bayesian network structure model, the standardized and processed formal research questionnaire data were imported into GeNIE4.0 software to learn the parameters of the causal relationship model for the vertical collusion chain of bidding for government investment projects.

Before parameter learning, the state of each observation indicator was set as Low, Middle, and High; the latent variables of external environment, competitive pressure, collusion gain, enterprise development, control system, policies and regulations publicity, and compliance consciousness were set as Yes and No, and the probability of occurrence of each state was the same. The processed standardized data were imported into the structural model after the state was set and the data were matched.

Due to the number of data samples and the characteristics of the research problem, and considering the need for subsequent analysis, the EM (Expectation Maximization) algorithm was chosen to learn the parameters. The EM algorithm has the advantages of simplicity and stable convergence, and is suitable for models that are complex or contain latent variables or missing data. The EM algorithm is an unsupervised expectation maximization algorithm, which combines the methods of great likelihood and iterative solving, and it can effectively realize the probability estimation of hidden variables. The final probability distribution

obtained is shown in Figure 3. Through parameter learning, it is found that the probability of the vertical collusion state occurring is 49%, the probability of it not occurring is 51%, and the risk of vertical collusion is high.

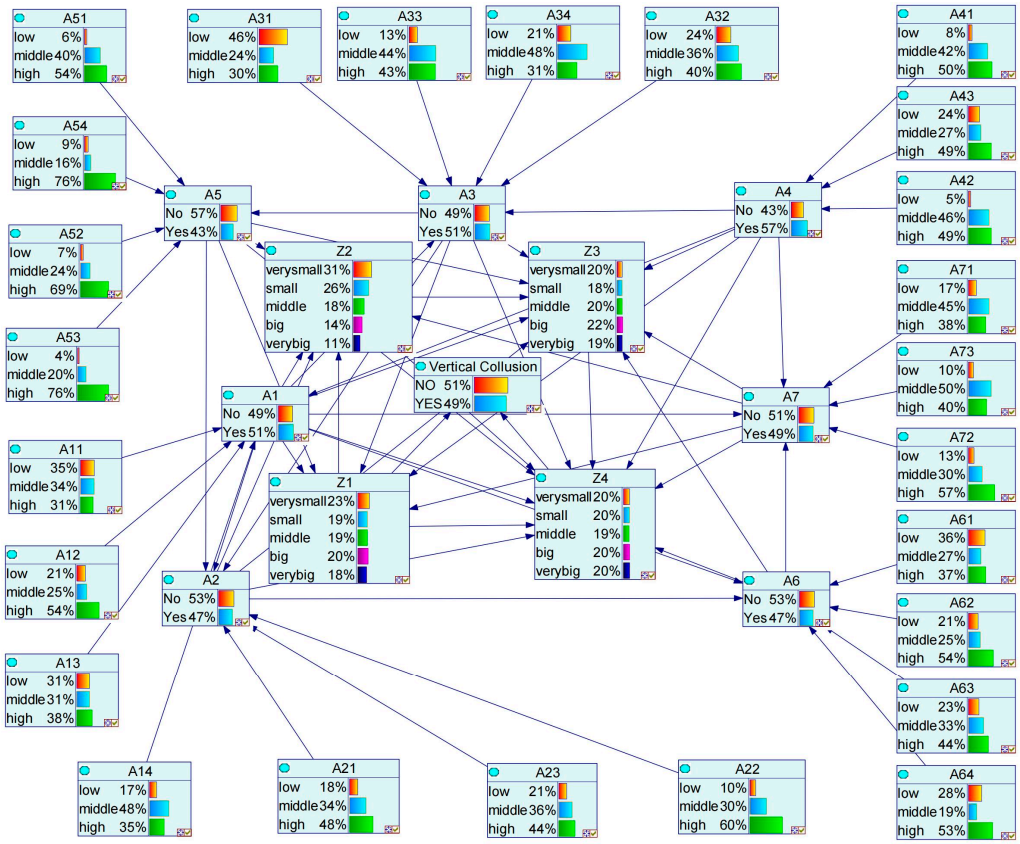


Figure 3. Plot of parameter learning results.

3.2. Identification of the Causal Chain and Key Node Analysis of Vertical Collusion

3.2.1. Identification of the Causal Chain

The vertical collusion causal chain in government investment project bidding is shaped by a variety of intertwined, recursive internal and external factors and the role of key subjects, ultimately leading to the formation of vertical collusion behavior causal chain. There are various paths for its formation. In order to study the paths through which vertical collusion passes between the cause and the subject, the study identifies the key chain that leads to the formation of vertical collusion, i.e., the chain of causation. Figure 4 shows the results when the "Yes" status for the occurrence of "vertical collusion" is set to 100%, and the relatively thicker ones in the figure are the causal chains.

Figure 4 shows that in the vertical collusion chain, the main body in the role of the cause of the main formation of three vertical collusion path, namely ① regulatory failure in the vertical collusion path due to external supervision of the main body by the collusive gains, the external environment, the pressure of competition, and compliance awareness of the impact of the formation of the "external supervision of the main body → response to the main body → vertical collusion"; ② internal and external collusion vertical collusion path due to the rights of the main body by the collusion of earnings, the external environment and the lack of publicity of policies and regulations, the external supervision of the main body by the collusion of earnings, the external environment, the pressure of competition, and compliance awareness of the formation of the "rights of the main body → external supervision of the main body → response to the main body of the → vertical collusion"; ③ rights out of control of the conspiracy path due to the rights of the subject by the

conspiracy proceeds, the external environment, and policies and regulations under the influence of insufficient publicity of the formation of the "rights of the subject → response subject → vertical conspiracy".

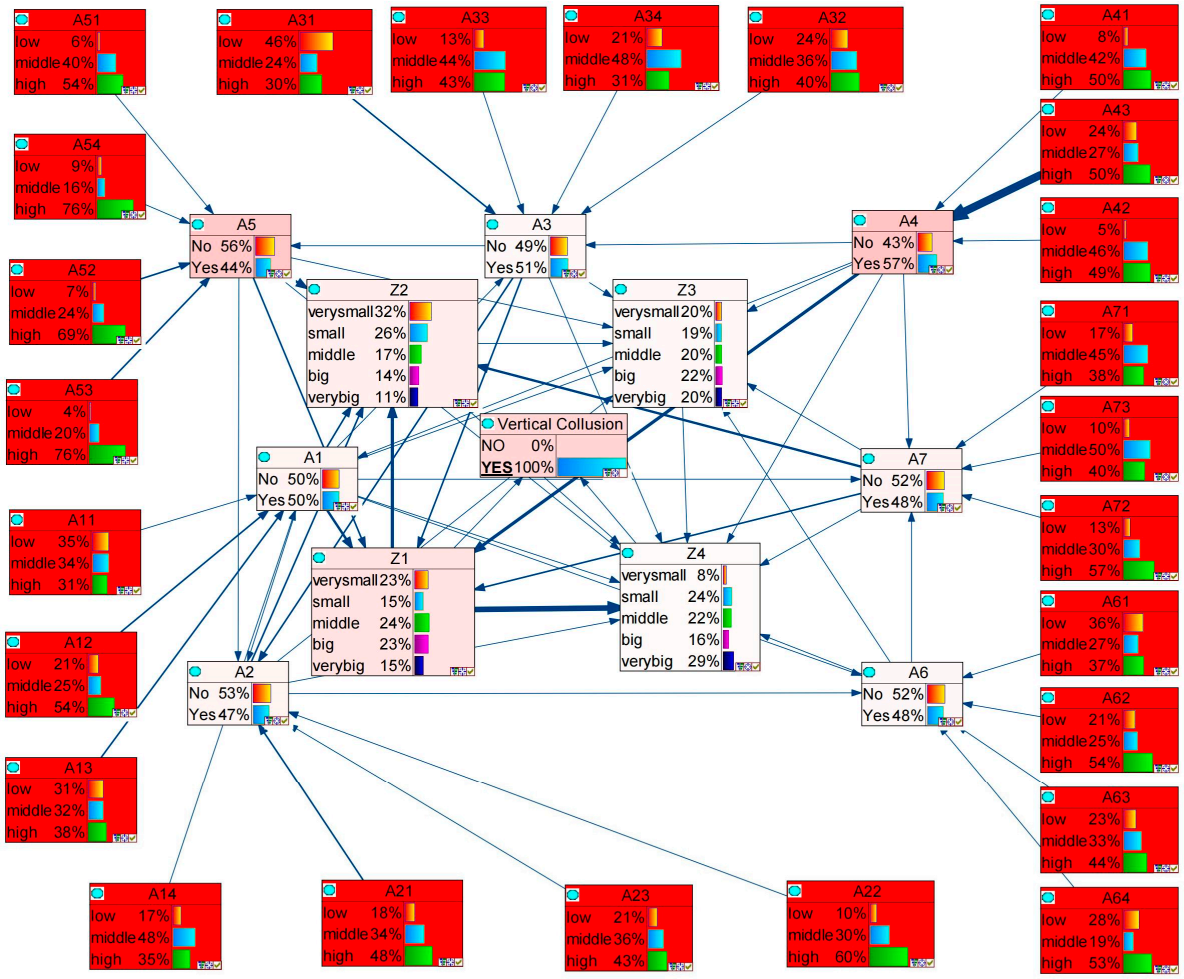


Figure 4. Causal chain analysis of vertical collusion in bidding for government investment projects.

From the cause of the active maintenance of the bidding market awareness, high project profits, acceptance of leadership guidance, non-participation in the conspiracy cannot obtain the project. These conditions, along with an imperfect system, plays a key role as the underlying causes in the vertical chain of conspiracy. It can be found that active maintenance of the bidding market consciousness, high project profit, accepting leadership guidance, and non-participation in the collusion to obtain the project are the most important causal factors in the vertical collusion chain.

3.2.2. Analysis of Key Nodes in Causal Chains

Reverse inference is the most important conditional probabilistic inference in Bayesian networks, and this section further analyzes the key nodes in the causal chain on the basis of identifying the causal chain. The study reasoned about the causal factors and the state of each subject in this case by pre-setting the probability of vertical collusion. The study further analyzes the key nodes in the causal chain formation on the basis of obtaining the causal chain. The study assumes that the state of vertical collusion in bidding for government investment projects is "Yes" and the probability of occurrence is 100%, and utilizes GeNIE to reason about the changes in the state and probability of the causal factors and subjects. The reasoning results are shown in Figure 5.

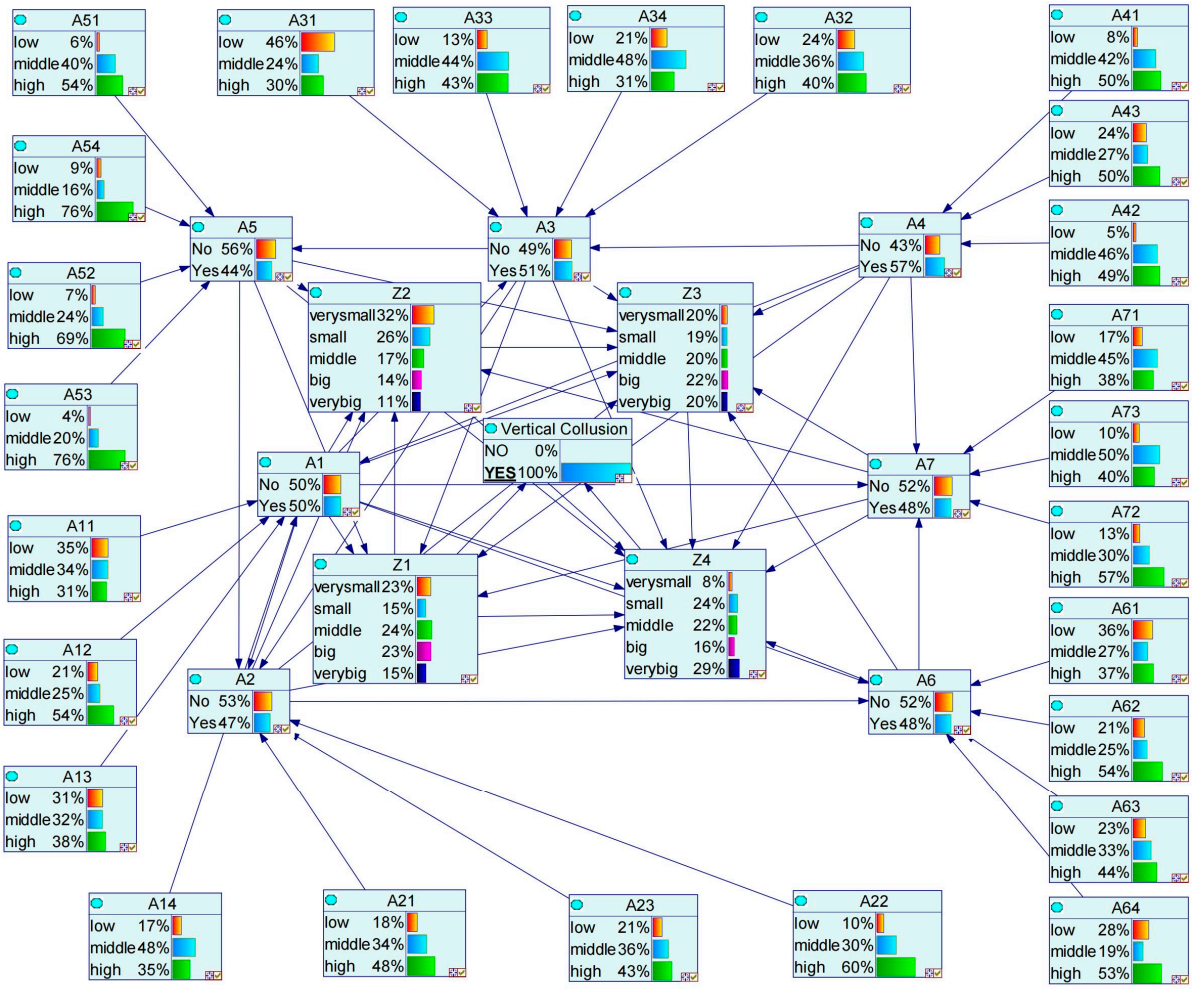


Figure 5. Reverse reasoning results of vertical collusion chain in bidding for government investment projects.

From Figure 5, it can be found that when the probability of the "Yes" state of the "Vertical Collusion" node is set to 100%, the probability values of the "Yes" states of the seven potential factors of the whole network are changed. States of the seven latent factors of the whole network are all changed in their probability values. The changes of latent variables and subject probabilities are shown in Tables 11 and 12.

Table 12. Change in probability of latent variables for reverse inference.

Latent Variables	Before Adjustment (%)		After Adjustment (%)		Status Change (%)
	Yes	No	Yes	No	
A1	51.33	48.67	50.24	49.76	−1.09
A2	47.08	52.92	47.18	52.82	0.10
A3	43.46	56.54	43.91	56.09	0.45
A4	47.46	52.54	47.63	52.37	0.17
A5	50.94	49.06	51.45	48.55	0.51
A6	56.62	43.38	57.30	42.70	0.68
A7	49.24	50.76	48.41	51.59	−0.83

From Table 12, it can be found that the causal factors with large changes in probability values are external environment, compliance awareness, policy and regulation publicity, control system, and collusive gain, while the competitive pressure and corporate competition have remained largely unchanged. Reverse inference results found that when the external environment deteriorates, the participating subjects' compliance awareness

declines and collusion gains are high. Even if the policy and regulation publicity and control efforts are increased, the probability of vertical collusion is still higher.

According to Table 13, it can be found that the subject probability value changes are larger for the right subject and the response subject, and the probability values of the external supervision subject and the internal supervision subject change less. This indicates that in the process of forming the vertical collusion chain, the right subject and the response subject have a greater impact and are the key subject nodes of the vertical collusion chain.

Table 13. Changes in the probability of the subject of a vertical collusion chain.

	Subjects	Right Holder	Internal Supervision Entity	External Supervision Entity	Responding Entity
Very small	Before	23.33	20.01	30.55	19.80
	After	23.13	20.00	31.67	8.47
	Change value	−0.20	−0.01	1.12	−11.33
Small	Before	18.83	18.44	26.45	19.99
	After	14.92	18.64	26.37	24.35
	Change value	−3.91	0.20	−0.08	4.36
Normal	Before	19.48	20.25	17.58	19.47
	After	24.25	19.92	16.78	22.20
	Change value	4.77	−0.33	−0.80	2.73
Large	Before	20.14	21.81	14.30	20.47
	After	22.88	21.78	13.75	16.21
	Change value	2.74	−0.03	−0.55	−4.26
Very large	Before	18.23	19.49	11.12	20.27
	After	14.82	19.66	11.43	28.77
	Change value	−3.41	0.17	0.31	8.50

Through analysis of Tables 12 and 13, it can be seen from the changes in various indicators that in order to control vertical collusion, it is necessary to strengthen control over key entities, build a favorable external environment, ensure fairness in the bidding market and strengthen management of vertical collusion.

3.2.3. Analysis of Key Factors for Causal Chain Control

Bayesian network modeling determines the degree of influence of different indicators on the vertical collusion chain through the effect of small changes in variables on the degree of change in other variables. Sensitivity analysis focuses on the relationship between local network parameters and global conclusions. In the analysis process of the causal relationship in the vertical collusion chain of bidding for government investment projects, the greater the sensitivity of the causal factor, the greater the sensitivity of the main body of the vertical collusion, indicating that the choice of the main body of the vertical collusion is more sensitive to the causal factor; the greater the sensitivity of the main body of the vertical collusion, the more responsive the main body's behavior is to the formation of the vertical collusion behavior. The study uses GeNIE to analyze the constructed Bayesian network on the basis of reverse inference and obtains the sensitivity analysis results as shown in Figure 6. Different color depths in the figure represent different degrees of influence of the causative agent and the subject, and darker colors represent a higher degree of influence.

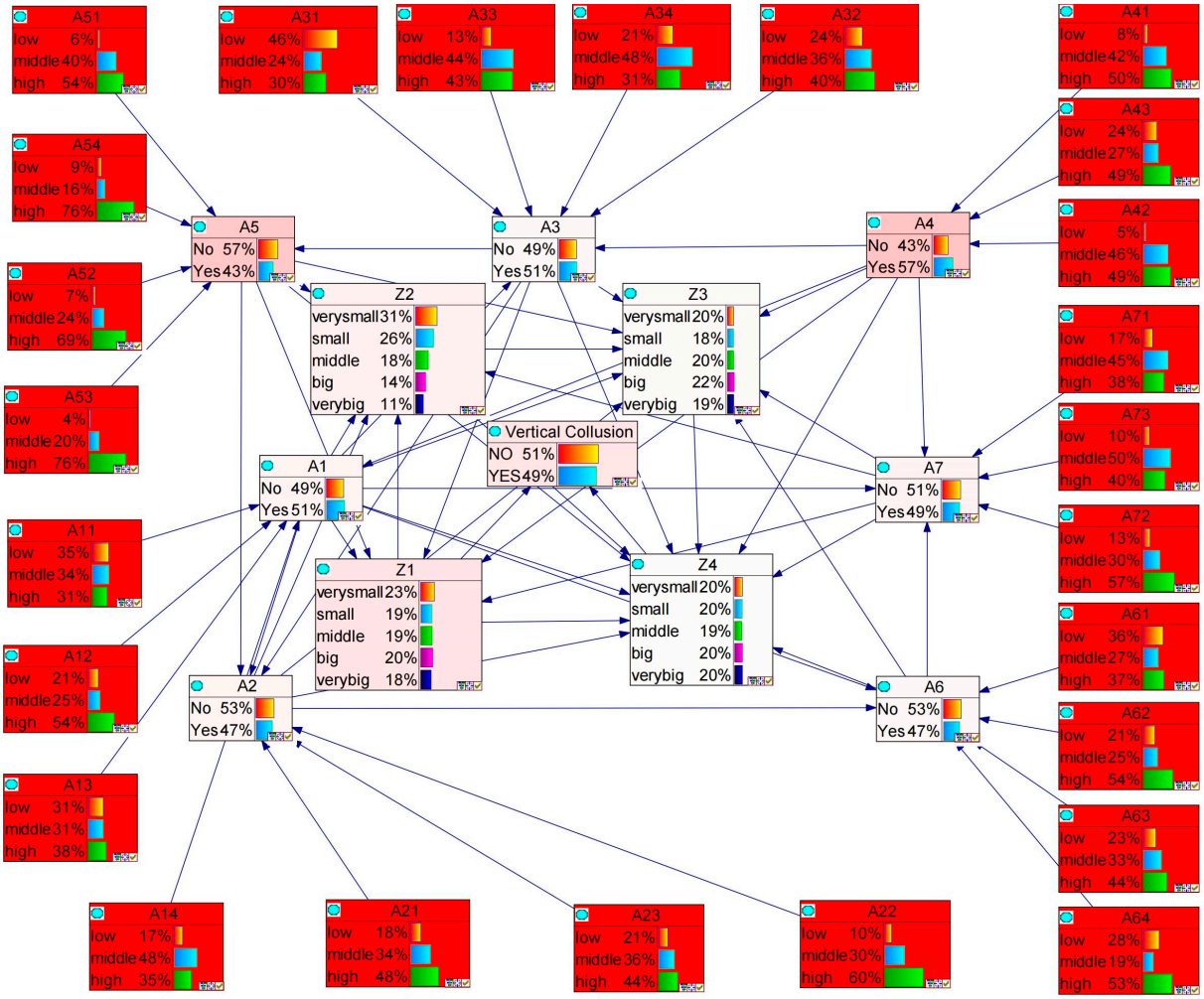


Figure 6. Bayesian network sensitivity analysis of vertical collusion causation in bidding for government investment projects.

The analysis results show that collusive gain, policy and regulation propaganda, compliance awareness, and external environment are the more sensitive points in the causative nodes, which also means that to realize the control of vertical collusion in bidding for government investment projects, the control of these factors can achieve better results; at the subject level, the subject of the right and the subject of the external supervision are the more sensitive nodes in the subject nodes and also the key subjects in the control process. In the subject level, the right subject and external supervision are the more sensitive nodes among the subject nodes and also the key subjects in the control process. As far as the observation indicators are concerned, all of them show high sensitivity, indicating that to realize the control of vertical collusion chain, it is necessary to consider and govern comprehensively.

4. Discussion and Conclusions

This paper analyzes the chain of causal links, i.e., the causal chain, which is formed by a variety of intrinsic and extrinsic factors that are intertwined and recursive, act on the key subjects and eventually lead to vertical collusion in the bidding of governmental engineering projects. This section utilizes the reverse inference analysis, sensitivity analysis, and causal chain analysis of a Bayesian network to explore the manifestation of a causal chain in the formation process of a vertical collusion chain and the key factors which

will provide help for the construction of chain-breaking strategies and implementation measures later. This chapter gets the following main conclusions:

(1) Four key entities—Right Holder, External Supervision Entity, Internal Supervision Entity, and Responding Entity—and 25 key factors have been identified.

(2) The identification of vertical collusion causal chain results in three main vertical collusion formation paths, namely: ① the vertical collusion path of regulatory failure due to the external supervision of the subject by the collusive gains, the external environment, the pressure of competition, and the lack of compliance awareness of the formation of the "external supervision of the subject → response to the subject → vertical collusion; ② the vertical collusion path involving internal and external collusion; ③the vertical collusion path including external collusion. The formation of vertical collusion occurs, due to the rights of the subject by the conspiracy proceeds, the external environment and the lack of publicity of policies and regulations, the external supervision of the subject by the conspiracy proceeds, the external environment, the pressure of competition, and the lack of awareness of compliance with the formation of "the rights of the subject → the external supervision of the subject → the subject of the response to the subject of the vertical collusion"; ③ rights out of control of the path of the conspiracy, i.e., because of the conspiracy path of uncontrolled rights, i.e., the "rights subject → response subject → vertical conspiracy" formed by the rights subject under the influence of conspiracy gain, external environment, and insufficient publicity of policies and regulations. The above results provide the basis for the construction of the chain-breaking strategies.

At the subject level, the right subject and the external supervisory subject are the key subjects in the control process; at the factor level, better vertical collusion control can be achieved by controlling the collusion gain, policy and regulation publicity, compliance awareness, and external environment.

Breaking the causal chain in bidding and tendering is a complex process. To improve efficiency, it is first necessary to analyze the key issues involved in breaking the causal chain and then establish control systems and strategies based on these key issues.

(1) Collusion opportunities are the decisive factor in the formation of vertical collusion.

Collusion opportunities include "the possibility of participating in vertical collusion" and "intrinsic collusion motives". The external environment provides the possibility for entities to participate in vertical collusion; institutional defects (including incomplete laws and regulations, insufficient enforcement, and regulatory loopholes) further increase the likelihood of participating in vertical collusion; simultaneously, collusion opportunities may also be actively created by participating entities, resulting in artificially created collusion opportunities. When the participants in government-funded engineering project bidding objectively have the possibility of engaging in vertical collusion and subjectively possess the intrinsic motivation for vertical collusion, their behavior is influenced by these factors. Under the influence of the "causal chain," this leads to the occurrence of collusive behavior. Therefore, to control vertical collusive behavior, it is necessary not only to eliminate the environmental factors enabling vertical collusion but also to eliminate the intrinsic motivations for vertical collusion.

(2) An unfair market competition environment is an important driving force behind the formation of vertical collusion.

In actual bidding processes, participating entities typically compare their own circumstances with those of others and assess whether they are in a fair environment. When participants perceive unfair treatment or unfair competition in the bidding process and cannot resolve such issues through conventional channels, they experience psychological

imbalance, which becomes a significant driving force behind the formation of vertical collusion. To control vertical collusion, it is necessary to create a fair market competition environment to eliminate the underlying motivations for such collusion.

Based on the identified causal chain and key factors, this study proposes targeted policy recommendations for regulatory authorities to curb vertical collusion in government investment project bidding.

For core entities, it is necessary to focus on constraining the Right Holder (Z1) and External Regulatory Entity (Z2). For right holders, they should be required to document core decisions in writing and publicly explain the reasons, while introducing third-party expert reviews to prevent abuse of power. For external regulatory entities, measures should be taken to prevent them from forming collusive relationships with project participants through long-term cooperation. A whistleblower reward system should be established to encourage internal supervisory entities to proactively expose collusive behavior.

Regarding key factors, interventions should focus on collusive benefits (A3), policy promotion (A6), and the external environment (A1). To weaken collusive motives, legal penalties should be strengthened to increase the cost of collusion, including imposing fines on violators and adding them to a credit blacklist. In terms of policy promotion, targeted education should be conducted. To optimize the external environment, a cross-departmental information-sharing platform should be established to monitor fund flows in real time and publicly disclose regulatory records, addressing issues such as selective enforcement and the concealment of interest transfers.

Although this study revealed the key pathways and influencing factors of longitudinal collusion by constructing a Bayesian network model, limitations remain that require refinement in future research: (1) This study employed Bayesian network analysis solely to examine causal relationships without comparative validation against other methods. Future research will incorporate cross-model comparisons to enhance the robustness of conclusions [34,35]. (2) During data collection, the preliminary interview phase involved a limited number of respondents. Although subsequent measures enhanced result reliability, potential information gaps remain. Future studies will expand the survey population. (3) Due to data collection constraints, this study did not sufficiently explore model applicability through specific case studies. Future research will conduct comparative analyses using representative cases to enhance the model's practical value.

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