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Analysis of Factors Affecting Prefabricated Building Quality Based on ISM-BN

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Abstract: In recent years, the rise of the domestic industry has boosted the use and popularity of prefabricated buildings. Prefabricated buildings differ significantly from traditional design, construction, and production models. However, due to the short development period of prefabricated buildings in China, the quality management of these new structures is still not mature, resulting in frequent project delays and failure. To improve quality management, this paper aims to establish an evaluation model of factors affecting prefabricated building quality. The 4M1E framework was used to categorize and generalize related quality factors. Then, GeNIe software was used to establish a visual Bayesian network quality factor evaluation model. The factors that need to be managed and given attention to in the prefabricated construction project were discovered using reverse reasoning, sensitivity, and critical factor analysis. The results indicated that among the multiple stages of prefabricated buildings, the construction stage has the greatest impact on the quality of buildings. C2(Insufficient sense of responsibility of construction personnel) is the most significant factor that needs to be controlled. In addition, this paper combined the ISM-BN model with actual engineering projects to identify key factors affecting the project's quality, demonstrating the model's applicability. The evaluation model of quality factors in prefabricated buildings was established. It can identify the underlying causes of quality issues in prefabricated buildings and control engineering quality at the source, acting as an effective guide for practitioners and enterprises.

Keywords: ISM-BN method; risk matrix method; quality management; 4M1E

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1. Introduction

Prefabricated buildings are formed by producing prefabricated components in factories and then assembling them on-site [1]. Compared to the traditional cast-in-place concrete building production mode, prefabricated buildings are more conducive to improving labor efficiency, have a higher degree of standardization, and require less on-site wet work. At the beginning of the 20th century, industrialized countries such as the United States and the United Kingdom were desperate to solve their housing needs, and the construction of prefabricated buildings was found to be one of the effective solutions [2]. The construction method of prefabricated buildings has significantly reduced construction time and cost, which has proven to deal with various housing problems. For instance, energy-efficient materials such as recycled steel can promote environmental sustainability for prefabricated buildings in many industrialized countries [3]. As a result, there has been a large growth in prefabricated buildings globally since World War II. Recently, prefabricated buildings have received significant attention from the Chinese government. On 27 September 2016, the State Council issued "Guiding Opinions on Vigorously Developing Prefabricated Buildings", aiming to continuously increase the proportion of prefabricated buildings and establish a quality supervision system [4]. Under the government's vigorous promotion, several provinces issued implementation opinions to promote the development of prefabricated buildings. In 2021, the market size of China's prefabricated construction industry reached RMB 1325.7 billion, and the newly started prefabricated building area totaled 740 million square meters, accounting for 24.5% of the newly built construction area (according to data from China Industrial Research Institute). In general, the positive development trend of prefabricated buildings has played a critical role in promoting the upgradation of the Chinese construction industry.

Quality management is one of the three primary objectives of project management, and the "assembly" feature of prefabricated buildings sets higher standards for quality. The construction process of prefabricated buildings involves activities not present in traditional construction projects. Therefore, the practice and assessment of the quality management of prefabricated buildings cannot follow the traditional model [5]. Firstly, the design of prefabricated buildings requires more experience and knowledge than traditional building projects. A lack of design experience and knowledge can lead to poor buildability and multiple design changes [6,7]. Secondly, producing prefabricated components requires industrialization, necessitating mature technology and a sound management mechanism [8]. Thirdly, prefabricated building projects have an additional transportation link. Unreasonable transportation plans, a lack of protection measures, unreasonable loading and unloading, etc., can all compromise the quality of prefabricated buildings [9]. Fourthly, the on-site construction of prefabricated buildings is more complex than traditional buildings. Poorly defined specifications, inadequate construction processes, and suboptimal personnel management can all negatively impact the quality of prefabricated buildings [10]. Therefore, in every link of a prefabricated building, high-level quality management is essential for the project to meet the required quality standards within a certain deadline. Currently, some shortcomings are present in the quality management of prefabricated buildings: (1) Inspection and testing are vital links. Some enterprises have not fully carried out inspection and testing. Prefabricated components cannot be guaranteed to meet the requirements [11]. (2) Prefabricated building projects involve multiple stakeholders. These stakeholders cannot achieve effective communication, resulting in the failure of the prefabricated building to progress smoothly, which affects the quality of prefabricated buildings [5]. (3) The lack of effective record files during the construction of prefabricated buildings makes it impossible to effectively track the quality of prefabricated buildings [12].

Prefabricated buildings are in a high growth stage, and many regional markets have huge demand. Some methods are used to evaluate the quality management level of assembled concrete buildings, generally identifying performance evaluation factors from different angles. For example, assessment models are established to provide data information on the design, off-site manufacturing, on-site construction, and transportation stages of prefabricated buildings, and to identify quality defects during the industrialization of prefabricated buildings [13]; Industry surveys of prefabricated construction companies are conducted, identifying quality-related factors from multiple dimensions, and posing the challenges facing prefabricated construction companies [14]; To systematically identify the factors that affect the quality of prefabricated buildings, structural equation modeling was used to develop an assessment method to measure the impact of these factors on assembled buildings [9]. Compared with traditional buildings, the construction environment and logistics management of prefabricated buildings are becoming increasingly complex, and traditional quality control methods cannot meet the advancement of projects. Scholars are currently researching quality management systems in the following general areas, for example, the development of automatic aggregate quality inspection techniques to improve inspection efficiency, which are used to inspect component geometric quality [15]; Prefabricated component information tracking and coordination system is established, basing on radio frequency identification (RFID) technology to realize the possibility of information interaction between prefabricated component supply chain and construction site [16]; The data of prefabricated component supply chain are often distributed on design, production, transportation, and other stages, proposing ontology-based and multi-intelligence decision support framework to achieve integration of multi-layer information to optimize multiparty coordination [17]. Scholars' research has some shortcomings in the quality management of prefabricated buildings. Scholars have used simpler mathematical models to explore the quality influencing factors, but have not explored the quality management of prefabricated buildings deeply enough.

By combining ISM and Bayesian methods, this paper aims to quantify the importance of the related factors. American scholar Warfield proposed the establishment method of interpretive structural model (ISM) to establish the relationship between the factors. ISM method can transform fuzzy or undefined models into clearly defined models so that complex systems had a fundamental factor layer, indirect factor layer, and direct factor layer after constructing the matrix [18]. Therefore, the ISM has been widely applied in influencing factor analysis, strategy research, and risk management. Another model used in this study was the Bayesian network (BN), also known as the belief network. It was a directed acyclic probabilistic model. The Bayesian network was created by Judea Pearl in 1985 to describe the causal relationship between variables and the exact impact probability. It is a quantitative and qualitative model [19]. The Bayesian network model has been proven capable of reliability, risk, and quality analyses. Judea Pearl and P. W. Jones summarized the inference mechanism of the Bayesian network, so the Bayesian network model gradually became a research field [20]. The ISM model requires manual construction of relationship graphs between variables and thus requires expertise and experience to guide it. The Bayesian model is only based on conditional probabilistic relationships and thus cannot handle complex causal relationships. Combining structural models and Bayesian network models can overcome their respective limitations. The ISM-BN model can infer both complex causal and probabilistic relationships.

The remaining sections were as follows: Section 2 explains the framework of methodology and the methods and steps of building the quality factor model. Section 3 explains the identification of quality factors, the collection of questionnaire data, and the establishment of a four-stage Bayesian network model. Section 4 includes the data analysis process, namely the reverse reasoning analysis, sensitivity analysis, and key factor analysis of the Bayesian network model, to ascertain the most significant quality factors that must be addressed. Section 5 discusses the measures to improve the level of prefabricated quality and the prospects for the future. Section 6 concludes the paper, by providing practical implications and suggestions for future research.

2. Research Method

2.1. Framework of Methodology

This study was conducted in three steps. First, quality factors affecting prefabricated buildings were identified and determined. By compiling and studying domestic and foreign literature on the quality management of prefabricated concrete buildings, the preliminary quality factors were identified, which were further revised and validated through six individual interviews with experts in the construction management field. Second, the interpretive structural model was used to present the quality factors in each of the four stages of a typical construction lifecycle, which determined the basic level of the Bayesian network. Individual interviews with another six experts were conducted to determine the relationship between each factor and the quality of prefabricated buildings. In the interviews, the experts were asked to rate their perceived degree of connections between the factors and quality, in which 0 represents no direct connection and 1 means that there is a direct connection between them. The average score of each factor was calculated, and factors with values equal to or greater than 0.5 were considered highly related factors. Table A2 in Appendix A shows the questionnaire used in the design stage.

Third, a Bayesian network model is established for the quality evaluation of prefabricated concrete buildings. The parameters of each node in the Bayesian network are obtained from online questionnaires (Tables A4–A7). The methodological framework of this paper is shown in Figure 1.

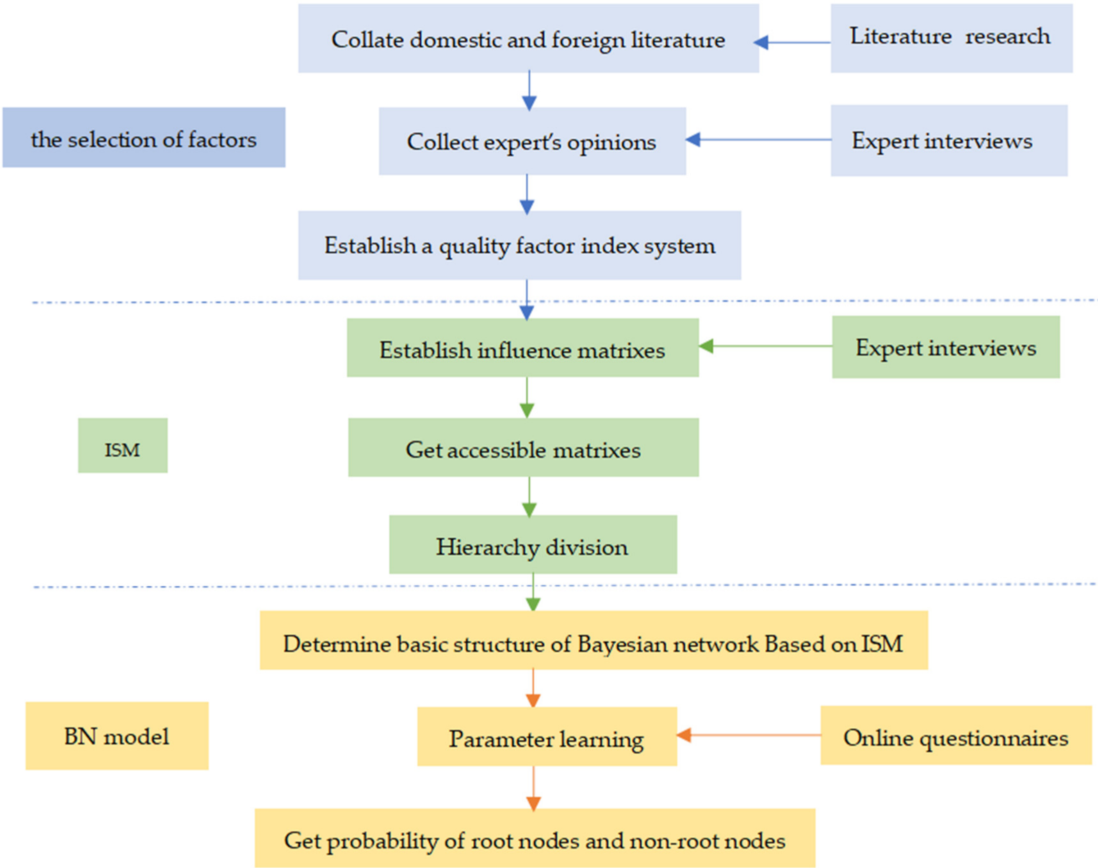

Figure 1. The method flow chart in the research.

2.2. ISM-BN Model

Warfield, an American scholar, proposed establishing an interpretive structural mode, referred to as the ISM method. It aims to convert a vague or undefined model into a clearly defined model so that a more complex system includes a fundamental factor layer, an indirect factor layer, and a direct factor layer that can be constructed [18]. Bayesian network, abbreviated as BN, was proposed by American scholar Pearl in 1988 as a directed acyclic graph consisting of arcs and nodes [20]. Since the combination of the two models can infer complex causal and probabilistic relationships, researchers started to establish integrated ISM-BN models in construction management [21]. In this research, the ISM-BN model of the quality factors of PC buildings was developed in five steps.

Step 1. The relationship between the quality factors of PC buildings and the impact matrixes was identified.

The influence matrixes reflected the direct relationship between quality factors, transforming complex thoughts into clear and intuitive models. After determining the factor index system of PC building quality in the framework of 4M1E, the adjacency matrixes of the quality factors in the four stages were determined according to the expert score.

The rules were as follows:

$$a_{ij} = \begin{cases} 0\, Factor\ a_i\ has\ no\ effect\ on\ a_j \\ 1 \quad Factor\ a_i\ has\ effect\ on\ a_j \end{cases} i \neq j \tag{1}$$

i was the row, j was the column.

Step 2. The accessible matrixes of the quality factors of PC buildings were determined.

The accessible matrixes represented whether there was a direct or indirect relationship among the quality factors of PC buildings. According to the rank of the adjacency matrix A of the quality factors, the unit matrix of the same order was added to A. Then, the reachable matrix R was obtained by power square operations. The calculation formula was as follows:

$$R = (A + I)^{k+1} = (A + I)^{k} \neq (A + I)^{k-1} \neq (A + I)^{k-2} \neq \ldots \neq (A + I) \quad (2)$$

k = 1, 2, 3 . . . , I was the same order unit matrix of A.

Step 3. According to the reachability matrix results of each stage (design, production, transportation, and construction), the leading sets, reachable sets, and common sets were obtained. Levels and ranks were divided based on common sets.

According to each iteration's common sets, each level's quality factors were determined.

The leading set P(B_i) represented the set of all indexes whose element value was 1 in the jth column of the reachable matrix R. The expression was:

$$P(B_i) = \{B_j \in B \,|\, b_{ij} = 1\} \quad (3)$$

The reachable set N(B_i) represented the set of all indexes whose element value was 1 in the ith row of the reachable matrix R. The expression was:

$$N(B_i) = \{B_i \in B \,|\, b_{ij} = 1\} \quad (4)$$

The common set M(B_i) represented the intersection of the leading set and the reachable set. The expression was:

$$M(B_i) = P(B_i) \cap N(B_i) \quad (5)$$

Step 4. The BN model of PC buildings' quality factors was drawn in four stages in design, production, transportation, and construction, respectively, based on the hierarchical relationship of the quality factors divided by ISM.

The GeNIe 3.0 software was employed to draw the BN model in order to fully quantify the hierarchical relationship model of quality factors obtained by ISM. The variable nodes of the BN were divided into parent and child nodes. The variables without parent nodes were root nodes, and the variables without child nodes were leaf nodes.

$$P(A = ST1 | B = ST0,\ C = ST0) = \frac{P(A = ST1, B = ST0, C = ST0)}{P(B = ST0, C = ST0)} \quad (6)$$

Step 5. Four stages' of Bayesian networks of PC buildings were analyzed.

The posteriori probability analysis, sensitivity analysis, and key factor analysis were carried out for BN in the design, production, transportation, and construction stages, respectively. By comparing the three kinds of analysis results, the corresponding measures for improving the quality management of prefabricated buildings were provided.

3. Model Building

3.1. Selection of Quality Influencing Factors

Many scholars have conducted several practical investigations on the quality management of prefabricated buildings [22,23]. Most of the research on the quality management of prefabricated buildings focused on a single stage, multiple stages, and stakeholders. The following scholars mainly explored the quality management level of prefabricated buildings at a single stage. Li et al. analyzed the development status of prefabricated building production in Hong Kong, highlighting information gaps and insufficient communication between designers and construction stages as weaknesses [24]. Chen analyzed the prefabricated component production process and found issues such as insufficient use of technology, lack of skilled personnel, and poor storage environments affecting the quality [25]. Li et al. pointed out that in the construction management stage, attention should be paid to recruiting experienced technical personnel and the particularity of the connection of prefabricated components [26]. Ren identified quality risk factors of the construction stage, emphasized construction personnel's awareness, and highlighted the importance of a reasonable plan for project success [27]. Guo built an SD quality risk model and analyzed that the factors that had the greatest impact on the quality of prefabricated construction were management and implementation factors, followed by environmental factors [28]. Deng et al. established a quality risk assessment model, highlighting the professionalism of production personnel, production equipment quality, and standard system integrity as key factors affecting component quality [8].

Some scholars had considered the whole construction process and sorted out the quality factor indicators from the design to the construction stages. Su et al. identified the factors that impact prefabricated building quality, including industrial workers' technology lack and environmental factors affecting the component strength (pH) [29]. Wang established a risk quality evaluation model encompassing design, production, transportation, and construction stages, then proposed measures to deal with quality risks: pay attention to the skills of professionals, strengthen the quality inspection of components entering the site, and enhance the awareness of quality supervision [21]. Qu summarized quality factors through expert discussion and questionnaires, identifying issues such as inconsistent standards and specifications, lack of professional cooperation, and low construction employee quality [30]. Chen et al. used system dynamics to establish a quality chain control model, highlighting the impact of design scheme rationality, transport personnel professionalism, and construction scheme rationality on the prefabricated building quality [31]. Wen established a production and construction evaluation system, identifying issues such as prefabricated buildings' lack of design standardization, unsatisfactory component production technology, unreasonable transportation plan, and insufficient professional practitioners [32]. Gan et al. identified quality as a key issue affecting the promotion of prefabricated buildings, highlighting the lack of component production standards and specifications, quality management systems, and technical guidelines for the project construction [7]. Dong identified construction quality factors from the aspects of components, construction preparation, equipment, and management coordination. Key factors were a lack of component production experience and rationality, as well as insufficient coordination between the construction party, manufacturer, and designer [33]. Xia et al. identified 25 quality factors based on prefabricated component production, transportation, storage, and hoisting stages, with transportation and storage having the greatest impact on component quality [9]. Wang et al. explored key risk factors of prefabricated buildings in China, including factory management, transportation planning, component strength, and housing quality monitoring technology [23].

In addition, some scholars evaluated the quality management level of prefabricated buildings from the stakeholders' perspective. Tao et al. evaluated stakeholders' impact on prefabricated building quality defects, finding that unreasonable construction personnel operation and ineffective quality inspections during construction were major factors [5]. Peter et al. interviewed contractors and identified obstacles to quality management implementation, including the lack of skilled workers, unreasonable project deadlines, and the lack of supervision [34]. The screening of factors through the literature revealed that most of the literature is lacking in the breadth of research on the quality of prefabricated buildings and uses simpler models in the quantification of factors.

An extensive literature review has resulted in the identification of a total of 36 quality factors, which can be matched into four stages of a typical construction project, namely design stage, prefabricated component production stage, transport stage, and construction stage. The factors were further classified into five dimensions according to the 4M1E framework, which includes man, material, machine, method, and environment. 4M1E method is an important analytical tool to study quality-related problems, and it is widely used to summarize and correct significant influencing quality factors in the field of quality management [35]. After that, six individual interviews were conducted with experts in the construction management field to verify and supplement the identified quality factors. All six experts have rich professional knowledge and hands-on experience in prefabricated concrete buildings, with four academics and two industrial practitioners. All six experts have master's degrees and above. Among them, four academics are engaged in research related to assembled buildings and have an excellent understanding of the local development of assembled buildings. Two industry practitioners are engaged in the structural technology of prefabricated buildings and have published several patents, who comprehensively understand the existing problems of prefabricated buildings. As shown in Table 1, the factor indexes affecting building quality under the framework of 4M1E were obtained after expert interviews. After modification and supplement, 43 quality factors were finally obtained.

Table 1. Factors affecting prefabricated building quality.

Stage	4M1E	Quality Factors	Serial Number	Source
Design stage	Man	Lack of precast design skills or experience	D1	[5,21]
		Insufficient responsibility of designers	D2	[30,36]
		Inadequate communication and coordination among professional designers	D3	[21,31]
		Insufficient communication between designers and other stakeholders	D4	[7,24]
	Method	Split design is unreasonable or not in place	D5	Expert interview
		Design standardization is not high	D6	[5,30,32]
		Lack of coordination between traditional design and prefabricated design	D7	Expert interview
		Lack of coordination between prefabricated design and construction plan	D8	[24,32]
	Environment	Design time is tight	D9	[7,34]
Prefabricated component production stage	Man	Relevant staff have weak quality awareness	P1	[32,36]
		Insufficient professional competence of production personnel	P2	[8,25,29]
	Material	Insufficient quantity of raw materials (such as steel bars, cement not in the prescribed quantity)	P3	Expert interview
	Machine	Production equipment does not meet the standard	P4	[8,21]
	Method	The curing conditions do not meet the requirements (standard curing room conditions)	P5	[5,8]
		Unreasonable ratio of raw materials	P6	Expert interview
		Lack of technical specifications and standards for component production	P7	[7,8,33]
		Lack of production quality management information system	P8	[24,25]
		The production process cannot meet the quality requirements	P9	[5,31]
		Components not stored according to standard (industry standard)	P10	[25,33]
	Environment	Workshop temperature and humidity do not meet the requirements	P11	[5,29]
		Production time is tight	P12	[21,34]
Transport stage	Man	Transport personnel are not professional enough	T1	[23,31]
		Insufficient sense of responsibility of transport personnel	T2	[26,36]
	Machine	Unreasonable selection of transport tools	T3	[9,32]
		Unreasonable selection of hoisting tools	T4	[9,32]
	Method	Unreasonable shipping sequence of prefabricated components	T5	Expert interview
		Unreasonable transportation route planning	T6	[5,8,37]
		Improper loading and unloading of prefabricated components	T7	[5,9,32]
		Prefabricated components transportation protection measures are not in place	T8	[23,31]
	Environment	The transportation distance is too long	T9	[23,31]

Table 1. *Cont.*

Stage	4M1E	Quality Factors	Serial Number	Source
Construction stage	Man	Insufficient practical experience of construction workers and managers	C1	[28,29,34]
		Insufficient sense of responsibility of construction personnel	C2	[26,27,36]
		Inadequate communication between various units and on-site construction personnel	C3	Expert interview
		Insufficient quality and level of supervisors	C4	[21,30]
		Prefabricated components are checked careless	C5	[21,30]
	Material	Insufficient connection strength of prefabricated components (e.g., insufficient grouting strength, insufficient bolt strength)	C6	[23,26]
	Machine	Lack of construction quality inspection tools	C7	[21,23]
	Method	Instructions for on-site assembly and construction are not detailed or accurate	C8	[7,21]
		Unreasonable construction schedule	C9	[5,30]
		Improper construction practices	C10	[5,27,29]
		Component installation accuracy is not enough	C11	Expert interview
		Improper stacking of prefabricated components	C12	[9,21]
	Environment	Construction workers lack reasonable working surfaces	C13	[28,31]

3.2. Data Collection

Based on the principle of risk matrix method, the questionnaire (Tables A4–A7 in Appendix A) was designed to classify the risk level of each quality factor. Then, the conditional probability of the nodes of the Bayesian network model was evaluated. Questionnaires were distributed to professionals who work as designers, contractors, and clients in prefabricated building projects. The questionnaire survey was conducted over 14 days, obtaining 136 valid questionnaires (160 total questionnaires distributed). The questionnaires with extreme response bias (i.e., participants repeatedly choose an extreme answer value to answer a question in a questionnaire) were considered invalid and thus excluded from the data collected. The criteria for the selection of the samples include: (1) they must be academics, engineers, or managers who have hands-on working experience in prefabricated construction projects; and (2) they must have experienced at least one prefabricated building project within the last three years and be familiar with the recent development of prefabricated buildings. Table 2 showed participants' background information (professional title, years of working, educational background). The results showed that most respondents (71.3%) have intermediate or higher professional titles, and more than half (61.8%) have at least 8 years of work experience, suggesting that the sample statistics in this paper are reliable.

Table 2. Background information of the questionnaire.

Constitution	Classification	Number
Professional title	Primary	23
	Intermediate	43
	Sub-senior	31
	Senior	10
Years of working	Less than 3 years	29
	3 to 7 years	23
	8 to 12 years	31
	13 to 17 years	24
	More than 18 years	29
Educational background	Junior college	17
	Undergraduate course	95
	Master's degree	19
	Doctor	3

As shown in Tables A3–A7 in Appendix A, respondents scored the indicators according to the score table of factors affecting prefabricated building quality. This questionnaire was administered on a 5-point Likert scale. As shown in Table 3, scores 1–5 represent hardly happens (virtually no impact), less frequent (less impact), general, more frequent (less impact), and most frequent occurrences (serious impact). This paper obtained the scores of factors affecting quality in the degree of loss and probability of occurrence. As shown in Figure 2, the statistics were transformed by the risk matrix method and classified into three levels: low risk, medium risk, and high risk.

Table 3. Levels of score table.

Score	1	2	3	4	5
Probability of occurrence Degree of influence	Hardly happens Virtually no impact	Less frequent Less impact	General General	More frequently Less impact	Most frequently occurrences Serious impact

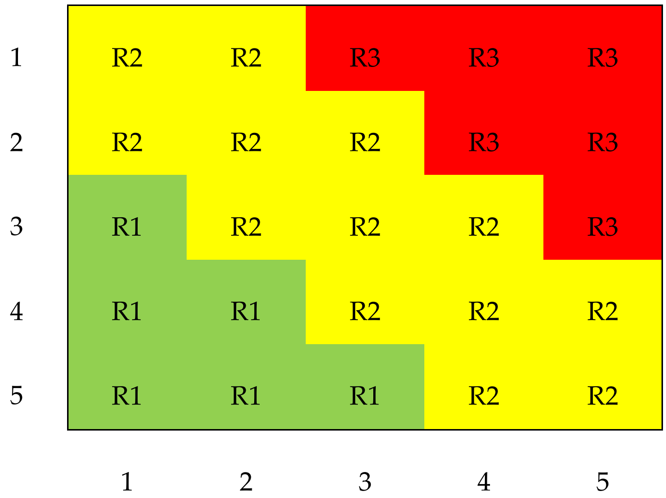

Figure 2. Risk matrix chart.

3.3. Establishment of ISM-BN Model

3.3.1. Calculating Reachable Matrix

The reachable matrix was the basis for determining the relationship between quality factors. Before calculating the reachable matrix, it was necessary to establish the adjacency matrix. Due to it being difficult determining the direct or indirect relationships between quality factors based on one's own experience and intuitive judgment, the expert score method was used in this research. In this interview, six experts were found to judge the relationship between factors. The basic information of these six experts is as follows: one of them is an associate professor (who has published many papers and presided over many city and hall level projects), two senior engineers (who are both chief engineers of their respective units and have published many patents), one intermediate engineer (who has participated in the construction of many assembled concrete building projects and has been on the front line for a long time), and two lecturers (who are both PhD graduates and have published more than ten academic papers). These experts are all engaged in project management and have a good understanding of prefabricated construction quality problems. Specifically, experts were required to evaluate the relationship between quality factors a_i and a_j. The evaluation standard was as follows: when there is a direct relationship between a_i and a_j, the evaluation is divided into 1. When there is no direct relationship between a_i and a_j, the evaluation is divided into 0 (according to the scores of each expert, the average score of each relationship was calculated, and the relationship equal to or greater than 0.5 was judged to be relevant). According to the comprehensive evaluation of experts, the adjacency matrixes of design, production, transportation, and construction stages were determined. Taking the design stage as an example, Table 3 showed the adjacency matrix of the quality factor in this stage.

Based on the results of the adjacency matrix in the design stage shown in Table 3, the adjacency matrix was adjusted and iterated according to the steps in Section 2.2 The reachability matrix of the design stage was shown in Table 4. The adjacency matrix in Table 4 and the reachable matrix in Table 5 corresponded to the factors affecting the quality of the design stage in Table 1. Therefore, the structural model of this stage was established by dividing the reachable matrix of the design stage. The steps of building the structural models in the production, transportation, and construction stages were similar to those in the design stage. The reachability matrixes of the remaining three stages were shown in Appendix A (Tables A8–A10).

Table 4. Adjacency matrix in the design stage.

	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**
D1	0	0	0	0	0	0	0	0	0
D2	0	0	1	1	0	0	0	0	0
D3	0	0	0	0	1	0	0	0	0
D4	0	0	0	0	0	0	0	1	0
D5	0	0	0	0	0	0	0	0	0
D6	0	0	0	0	1	0	1	0	0
D7	1	0	0	0	0	1	0	0	0
D8	0	0	0	0	0	0	0	0	0
D9	0	0	1	1	0	0	1	0	0

Table 5. Reachability matrix in the design stage.

	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**
D1	1	0	0	0	0	0	0	0	0
D2	0	1	1	1	1	0	0	1	0
D3	0	0	1	0	1	0	0	0	0
D4	0	0	0	1	0	0	0	1	0
D5	0	0	0	0	1	0	0	0	0
D6	1	0	0	0	1	1	1	0	0
D7	1	0	0	0	1	1	1	0	0
D8	0	0	0	0	0	0	0	1	0
D9	1	0	1	1	1	1	1	1	1

3.3.2. Determining Basic Structure

The structural models can be established by dividing the reachable matrixes. The division results of the accessibility matrix of design, production, transportation, and construction stages are shown in Figure 2. Based on the analysis of the accessibility matrix and the establishment method of the structural model, the structural models for each stage can be divided into three layers: the fundamental factor layer, the indirect factor layer, and the direct factor layer. Taking the design stage as an example, D6 (Design standardization is not high), D9 (Design time is tight), and D2 (Insufficient responsibility of designers) were three factors in the fundamental factor layer, which had a direct impact on the indirect factors including D3 (Inadequate communication and coordination among professional designers), D4 (Insufficient communication between designers and other stakeholders) and D7 (Lack of coordination between traditional design and prefabricated design). D1 (Lack of precast design skills or experience), D5 (Split design is unreasonable or not in place), and D8 (Lack of coordination between prefabricated design and construction plan) were three factors that had a direct effect on the target node. The structural models of production, transportation, and construction stages are shown in Figure 3 (D represents quality problems in the design stage; P represents quality problems in the production stage of prefabricated components;

T represents quality problems in the transportation stage; C represents quality problems in the construction stage; and Q represents quality problems in prefabricated buildings).

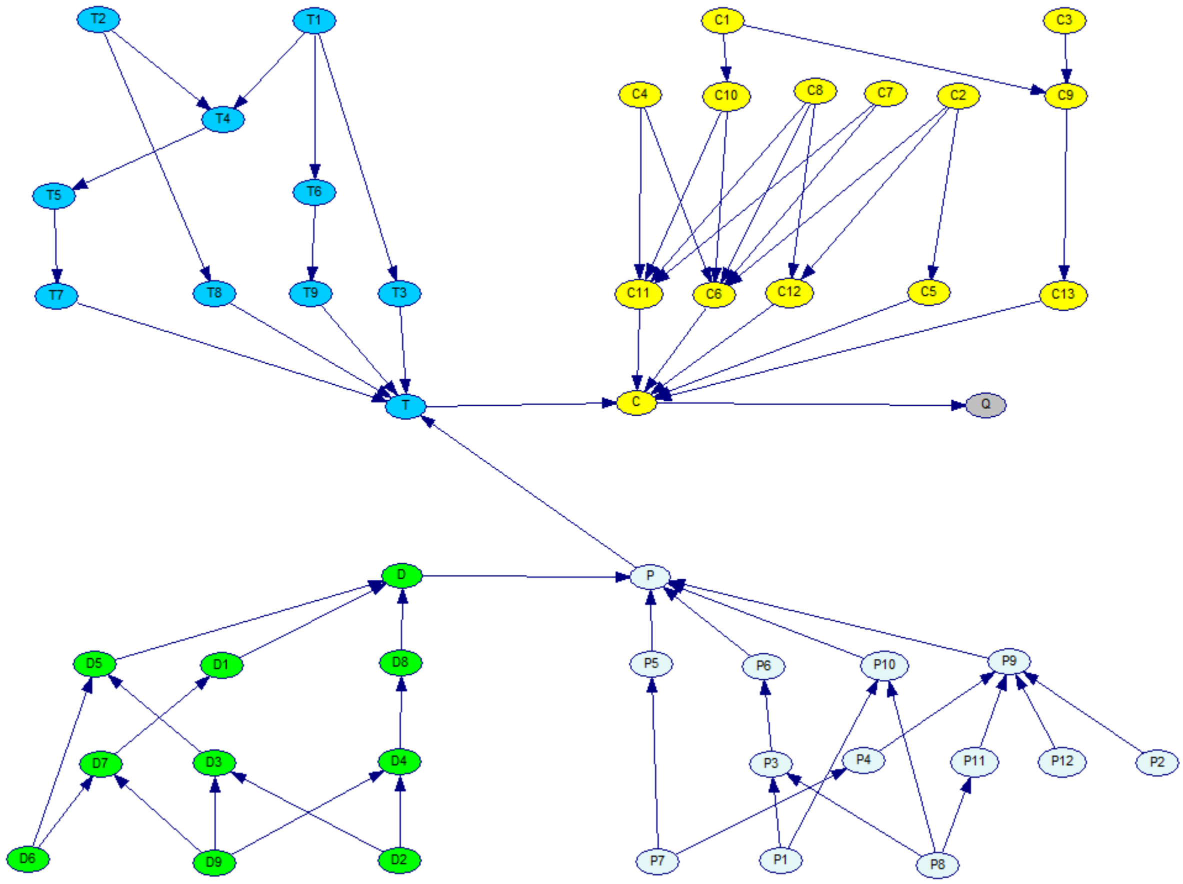

Figure 3. Bayesian network structure.

4. Discussions and Results

4.1. Node Distribution of the Model

Figure 4 presents a model of factors affecting the quality of prefabricated buildings. Compared to similar articles in the field [5], this paper deals with more factors and clearly divides the prefabricated building into four stages. By examining the distribution probability of nodes in each stage, the design stage had the lowest probability of quality problems, with a high-risk probability of only 13%. In the production stage of prefabricated components, the probability of quality problems at high risk was 24%, ranking third among the four stages. In the transportation stage, the probability of quality problems at high risk was 25%, ranking second among the four stages. Finally, in the construction stage, the probability of quality problems at high risk was 30%. Compared with the factors in the previous three stages, the high-risk probability values of C1 (Insufficient practical experience of construction workers and managers), C6 (Insufficient connection strength of prefabricated components), and C11 (Component installation accuracy is not enough) were higher. The factors affecting the overall quality of prefabricated concrete buildings were mainly in the construction stage.

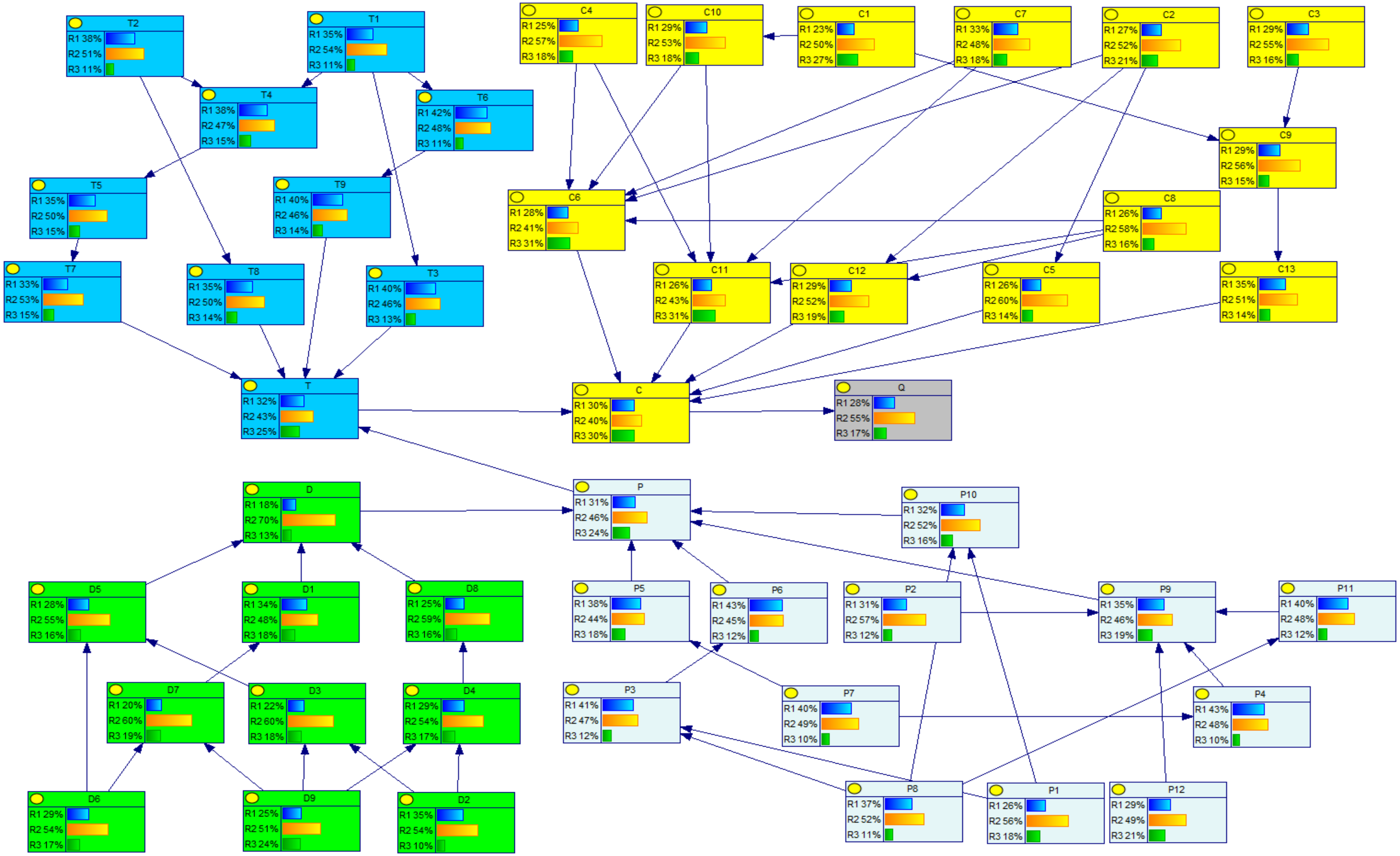

Figure 4. ISM-BN model.

Note: The Bayesian network nodes depicted in Figure 4 are approximations of the exact values. For precise values, please refer to Table 6.

Table 6. Exact value of the node.

	R1	R2	R3
D	0.1776	0.6969	0.1255
D1	0.3374	0.4842	0.1784
D2	0.3528	0.5426	0.1046
D3	0.2178	0.6040	0.1782
D4	0.2907	0.5442	0.1651
D5	0.2838	0.5518	0.1644
D6	0.2871	0.5426	0.1703
D7	0.2047	0.6039	0.1914
D8	0.2529	0.5886	0.1585
D9	0.2506	0.5061	0.2433
P	0.3069	0.4573	0.2358
P1	0.2579	0.5572	0.1849
P2	0.3090	0.5718	0.1192
P3	0.4126	0.4661	0.1213
P4	0.4252	0.4757	0.0991
P5	0.3821	0.4396	0.1783
P6	0.4309	0.4451	0.1240
P7	0.4039	0.4915	0.1046
P8	0.3674	0.5207	0.1119
P9	0.3453	0.4636	0.1911
P10	0.3190	0.5237	0.1573
P11	0.3962	0.4831	0.1207
P12	0.2944	0.4915	0.2141
T	0.3172	0.4305	0.2523
T1	0.3528	0.5353	0.1119
T2	0.3820	0.5061	0.1119
T3	0.4035	0.4620	0.1345
T4	0.3765	0.4697	0.1538
T5	0.3491	0.5049	0.1460
T6	0.4180	0.4755	0.1065
T7	0.3281	0.5267	0.1452
T8	0.3533	0.5048	0.1419
T9	0.4034	0.4606	0.1360
C	0.2990	0.4025	0.2985
C1	0.2287	0.4988	0.2725
C2	0.2652	0.5207	0.2141
C3	0.2944	0.5499	0.1557
C4	0.2506	0.5718	0.1776
C5	0.2582	0.5984	0.1434
C6	0.2828	0.4096	0.3076
C7	0.3309	0.4842	0.1849
C8	0.2579	0.5791	0.1630
C9	0.2950	0.5585	0.1465
C10	0.2940	0.5263	0.1797
C11	0.2590	0.4332	0.3078
C12	0.2856	0.5230	0.1914
C13	0.3459	0.5122	0.1419
Q	0.2808	0.5487	0.1705

4.2. Backward Reasoning Analysis

Backward reasoning analysis is also called reverse diagnostic reasoning. When the occurrence of the target node is determined, the probability of risk occurrence of other nodes is derived [38,39]. Table 7 shows the factors with a relatively high rate of change in the posterior probability test of the design stage, the component production stage, the transport stage, and the construction stage of the prefabricated building project.

Table 7. Results of backward reasoning.

Stage	Factors
Design stage	D1 D5 D6 D7 D8
Component production stage	P5 P6 P9
Transport stage	T3 T8
Construction Stage	C2 C5 C11 C12 C13

According to the factors listed in Table 6 and the backward reasoning analysis figures in Appendix B (Figures A1–A4), D1 (Lack of precast design skills or experience) and D8 (Lack of coordination between prefabricated design and construction plan) had a change rate of more than 1 for these two factors. Additionally, D5 (Split design is unreasonable or not in place), D7 (Lack of coordination between traditional design and prefabricated design), and D6 (Design standardization is not high) had relatively large change rates, which were significantly different from other factors in this stage. In the production stage, P5 (The curing conditions do not meet the requirements), P6 (Unreasonable ratio of raw materials), and P9 (The production process cannot meet the quality requirements) had relatively large change rates, while the change rate of other factors in this stage was significantly lower. The posterior probabilities for these three factors were notably different compared to the other factors in this stage. In the transportation stage, T3 (Unreasonable selection of transport tools) and T8 (Prefabricated components transportation protection measures are not in place) were the top two factors. The rate of change for these two factors was not significantly different from that for other factors in this stage. In the construction stage, C2 (Insufficient sense of responsibility of construction personnel), C5 (Prefabricated components are checked carelessly), C11 (Component installation accuracy is not enough), C12 (Improper stacking of prefabricated components), and C13 (Construction workers lack reasonable working surfaces) had a relatively large rate of change and ranked among the top five factors. The rate of change for factors in this stage was lower than that of the other three stages, but the posterior probability value of high risk was generally higher. The factors in the construction stage significantly impacted the overall quality of the prefabricated building.

4.3. Sensitivity Analysis

Sensitivity analysis can determine which factors have a small change but can cause quality problems at a particular stage [40,41]. In Bayesian network graphs, dark nodes are usually used to indicate high-sensitivity variables, while lighter nodes indicate lower-sensitivity variables. Table 8 shows the nodes with high sensitivity in the design, component production, transportation, and construction stages. The sensitive factor identification map of the four stages was shown in Appendix B (Figures A5–A8), with factors of higher sensitivity marked in dark color. In the design stage, D1 (Lack of precast design skills or experience), D8 (Lack of coordination between prefabricated design and construction plan), and D9 (Design time is tight) were highly sensitive factors at this stage. Therefore, design experience, coordination of schemes, and project deadlines had a greater impact on design quality. In the component production stage, P5 (The curing conditions do not meet the requirements), P6 (Unreasonable ratio of raw materials), P7 (Lack of technical specifications and standards for component production), P8 (Lack of production quality management information system) were high sensitivity factors at this stage. Therefore, production standards and methods, raw material ratios, and management systems had a greater impact on production quality. In the transport stage, T1 (Transport personnel are not professional enough), and T2 (Insufficient sense of responsibility of transport personnel) were highly sensitive factors. Therefore, practitioners' professionalism and sense of responsibility have a greater impact on the quality of transportation. In the construction stage, C2 (Insufficient sense of responsibility of construction personnel), C5 (Prefabricated components are checked careless), C8 (Instructions for on-site assembly and construction are not detailed or accurate), and C13 (Construction workers lack reasonable working surfaces) were highly sensitive factors at this stage. Therefore, the quality awareness of practitioners and the rationality of construction standards and construction schemes had a greater impact on construction quality.

Table 8. High sensitivity factor table.

Stage	Factors
Design stage	D1 D8 D9
Component production stage	P5 P6 P8 P7
Transport stage	T1 T2
Construction Stage	C2 C5 C8 C13

4.4. Critical Factor Analysis

Critical quality factor analysis can identify each stage's most approximate cause chain and critical risk path. The directed arc's width represents the influence intensity between the two nodes [42]. Table 9 displays the critical factors in the design, component production, transportation, and construction stages.

Table 9. Critical factor table.

Stage	Factors
Design stage	D2 D4 D7 D9
Component production stage	P3 P7 P8
Transport stage	T1 T2 T5 T4 T6
Construction Stage	C1 C2 C3 C9

Based on the factors listed in Table 9 and the critical factor analysis chart in Figure 5, we could obtain the nodes with the highest connection strength in the four stages by comparing the connection strength between the parent and child nodes. During the design stage, D7 (Lack of coordination between traditional design and prefabricated design) for D1 (Lack of precast design skills or experience) had the greatest effect intensity. Critical factors to consider at this stage include staff accountability and program coordination issues. During the production stage, P8 (Lack of production quality management information system) for P11 (Workshop temperature and humidity do not meet the requirements) had the greatest effect intensity. The critical factors at this stage mainly focused on production management issues and technical specifications. During the transport stage, T1 (Transport personnel are not professional enough) for T3 (Unreasonable selection of transport tools) had the greatest effect intensity. Critical factors to consider at this stage included the experience and sense of responsibility of staff and the rationality of the transportation plan. During the construction stage, C9 (Unreasonable construction schedule) for C13 (Construction workers lack reasonable working surfaces) had the greatest intensity. The critical factors at this stage were mainly focused on the staff's level of experience and responsibility and the issue of coordinating program management.

4.5. Results of Comparison

By comparing the three analyses (Table 10), C2 (Insufficient sense of responsibility of construction personnel) was the factor that require the most intensive control. This factor belonged to the construction stage. Therefore, project managers should strengthen staff training and enhance their quality awareness and sense of responsibility.

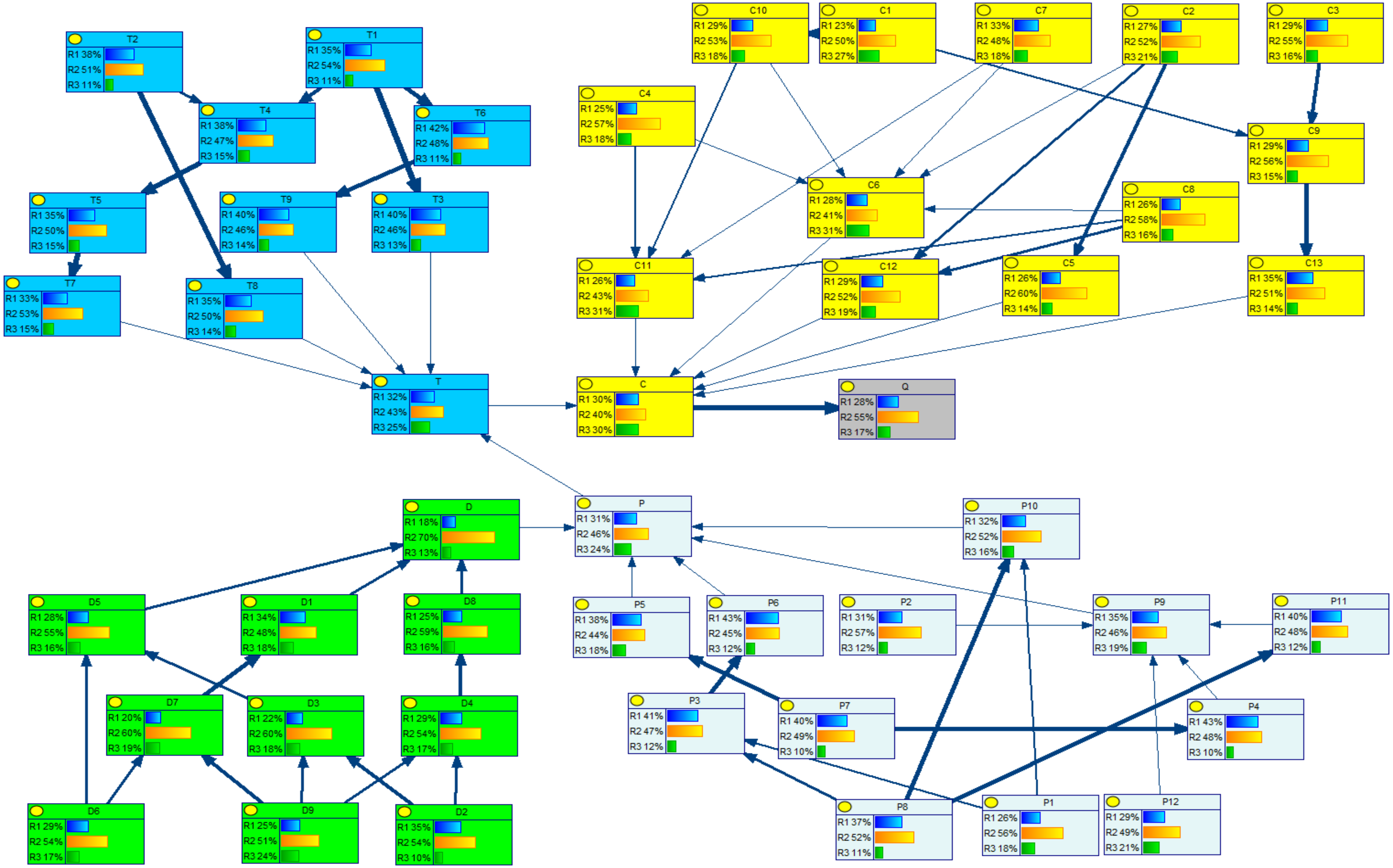

Figure 5. Critical factor analysis.

Table 10. Results of comparison.

	Backward Reasoning Analysis	Sensitivity Analysis	Critical Factor Analysis
Design stage	D1 D5 D6 D7 D8	D1 D8 D9	D2 D4 D7 D9
Component production stage	P5 P6 P9	P5 P6 P8 P7	P3 P7 P8
Transport stage	T3 T8	T1 T2	T1 T2 T5 T4 T6
Construction Stage	C2 C5 C11 C12 C13	C2 C5 C8 C13	C1 C2 C3 C9

Some quality factors need a little attention in each stage. In the design stage, attention should be paid to D1 (Lack of precast design skills or experience), D7 (Lack of technical specifications and standards for component production), D8 (Lack of coordination between prefabricated design and construction plan), and D9 (Design time is tight). In the production stage, attention should be paid to P5 (The curing conditions do not meet the requirements), P6 (Unreasonable ratio of raw materials), P7 (Lack of technical specifications and standards for component production), and P8 (Lack of production quality management information system). In the transport stage, attention should be paid to T1 (Transport personnel are not professional enough) and T2 (Inadequate responsibility of transport personnel). In the construction stage, attention should be paid to, C5 (Prefabricated components are checked carelessly), and C13 (Construction workers lack reasonable working surfaces). The results of this paper are partially similar to those of Tao Yu et al. [5] in that the human factors in the project have a greater impact on the quality of assembled buildings. However, this paper has a broader study of factors, and the influence of code standards, the rationality of design solutions, and the ratio of materials on the quality of prefabricated buildings is also significant.

5. The Case Study

5.1. Basic Information of the Project

Yingyuan Subdistrict Phase II Project is located on the south side of Shanghai Road and west of Huangpu River, with a prefabrication rate of 50%. The project consists of four 26-story residential buildings, one 18-story residential building, two 15-story residential buildings, 12 villas, basements, supporting rooms, garages, and ancillary facilities, totaling 105,400 m^2. Prefabricated parts and components include main and outer enclosure structures and inner and interior building components. On-site interviews and surveys were conducted by the relevant staff, who completed 30 questionnaires. Table 11 shows their educational background, unit nature, and years of employment.

Table 11. Basic information of relevant staff.

Constitution	Classification	Number
Nature of the unit	Design	8
	Construction	8
	Proprietor	3
	Supervision	2
	Others	9
Years of employment	Less than 3 years	4
	3 to 7 years	5
	8 to 12 years	7
	13 to 17 years	5
	More than 18 years	9
Education background	Junior college	3
	Undergraduate course	16
	Master's degree	9
	Doctor	1
	Others	1

5.2. Analysis of Quality Problems

The questionnaire analysis results of the project case were input into the Bayesian network quality evaluation model. Figure 6 obtained the critical factor distribution map for the project case. The analysis results, in this case, were consistent with the previous evaluation model analysis.

(1) The influence of the "employee" factor. The unprofessionalism of transportation personnel was primarily evident during the transportation stage. Therefore, adequate training and resources should be provided to the staff to equip transportation personnel with the necessary professional tools to effectively handle challenges encountered during transportation. For example, the local government can organize training sessions to clarify and unify design principles and industrial standards and specifications. In contrast, construction organizations should timely hold workshops or seminars to facilitate internal experience sharing and technical exchange among designer professionals. During the construction stage, inadequate staff experience and poor communication between different units and construction personnel were the main problems. Therefore, staff allocation should be performed well, and professional personnel should be hired to solve the technical problems at each link.

(2) The influence of "technical method or process" factors at each stage. Designing prefabricated structures may face issues of inconsistency with traditional modes or construction methods. Therefore, the type, connection method (e.g., bolting, welding, mortise, and tenon joints), and construction process of the assembled components need to be clarified in the design stage to ensure the smoothness of the subsequent stages. Clarifying the types of assembly components, connection methods, and construction processes helps designers and manufacturers work collaboratively in different project stages. Prefabricated components were prone to appearance quality defects, such as cracks, shape defects, and local uncompacted concrete. Therefore, a complete production management system should be established. Component production standards and specifications should be formulated. Unreasonable selection of transportation means or unreasonable transportation route planning may cause the loss of some components. This will reduce quality problems and scrap rates in production and improve productivity and resource utilization. Selecting transportation and hoisting tools according to the size and shape of the components was necessary to ensure the smooth progress of subsequent construction. Installing prefabricated components was a key process to ensure the quality of the construction stage—the installation involved flatness control, seam check, joint welding quality, etc. Therefore, the on-site assembly should be carried out in strict accordance with the drawing requirements and construction specifications. For the contractors and the owner, it improves the quality of the installation of prefabricated components during the construction stage, ensures the accurate positioning and stable connection of the components, and enhances the safety and stability of the overall building structure.

(3) The construction stage had the greatest impact on the quality of prefabricated buildings. The construction stage of prefabricated buildings should consider the building's durability, safety, and reliability. Therefore, attention should be paid to the acceptance of component quality, the inspection of concealed projects, and the reasonable arrangement of construction planned to ensure construction quality while improving efficiency and saving costs.

(4) In the case study of this project, the correlation between C9 (Unreasonable construction schedule) and its sub-node was clearly enhanced. The project's time-setting requirement was too high, and the construction period was short. The difficulty of construction was increased, resulting in a very tight project schedule. The construction plan was required to be modified or rearranged.

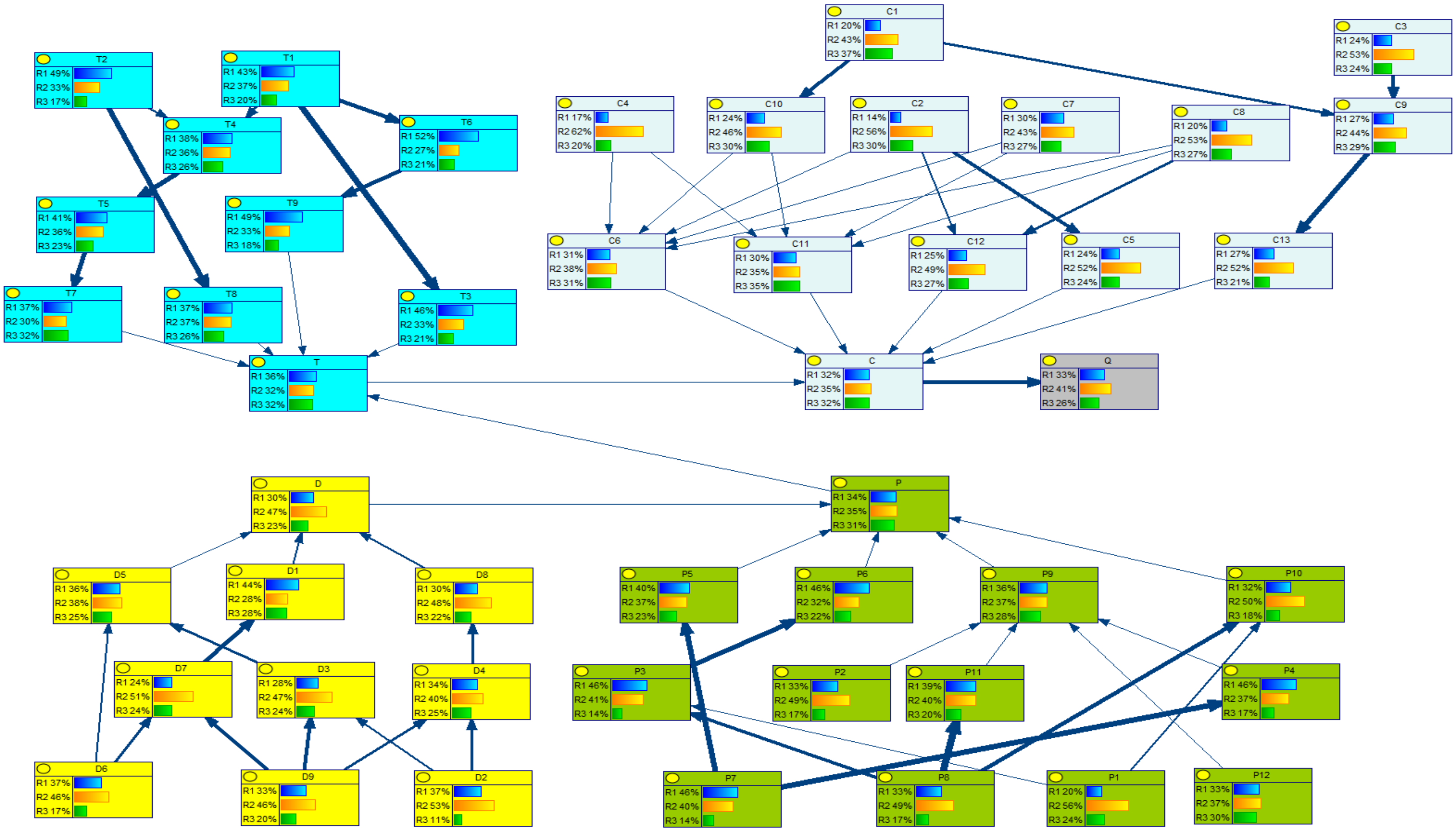

Figure 6. Quality Factor Evaluation Results of Project Cases.

Note: The Bayesian network nodes depicted in Figure 6 are approximations of the exact values. For precise values, please refer to Table 12.

Table 12. Exact value of the case node.

	R1	R2	R3
D	0.2999	0.4706	0.2295
D1	0.4376	0.2850	0.2774
D2	0.3656	0.5269	0.1075
D3	0.2843	0.4747	0.2410
D4	0.3407	0.4046	0.2547
D5	0.3623	0.3833	0.2544
D6	0.3656	0.4624	0.1720
D7	0.2440	0.5141	0.2419
D8	0.3031	0.4812	0.2157
D9	0.3333	0.4624	0.2043
P	0.3391	0.3484	0.3125
P1	0.2043	0.5591	0.2366
P2	0.3333	0.4946	0.1720
P3	0.4572	0.4072	0.1356
P4	0.4609	0.3669	0.1722
P5	0.3995	0.3671	0.2334
P6	0.4551	0.3248	0.2201
P7	0.4624	0.3978	0.1398
P8	0.3333	0.4946	0.1720
P9	0.3579	0.3655	0.2766
P10	0.3206	0.5016	0.1778
P11	0.3948	0.4009	0.2043
P12	0.3333	0.3656	0.3011
T	0.3608	0.3228	0.3164
T1	0.4301	0.3656	0.2043
T2	0.4946	0.3333	0.1721
T3	0.4600	0.3335	0.2065
T4	0.3819	0.3578	0.2603
T5	0.4080	0.3584	0.2336
T6	0.5209	0.2713	0.2078
T7	0.3739	0.3013	0.3248
T8	0.3700	0.3657	0.2643
T9	0.4898	0.3307	0.1795
C	0.3224	0.3534	0.3242
C1	0.2043	0.4301	0.3656
C2	0.1398	0.5591	0.3011
C3	0.2366	0.5269	0.2365
C4	0.1720	0.6237	0.2043
C5	0.2378	0.5198	0.2424
C6	0.3062	0.3829	0.3109
C7	0.3011	0.4301	0.2688
C8	0.2043	0.5269	0.2688
C9	0.2660	0.4396	0.2944
C10	0.2388	0.4564	0.3048
C11	0.2991	0.3479	0.3530
C12	0.2450	0.4862	0.2688
C13	0.2684	0.5248	0.2068
Q	0.3269	0.4142	0.2589

6. Conclusions

The factors affecting prefabricated building quality were determined through relevant literature research and expert interviews. Then, the ISM-BN model was established to visualize the relationship between nodes. The model parameters were learned to obtain the probability of each node. The qualitative and quantitative combination of the ISM-BN model could help practitioners fully identify factors affecting project quality during implementation and formulate measures to improve prefabricated buildings' quality. Through the analysis of the quality problems of a prefabricated building project in Nantong, it is found that the evaluation results of quality factors established in this case are consistent with the results of the previous analysis, indicating that the model is applicable in general prefabricated building projects.

According to the reverse reasoning analysis, sensitivity analysis, and key factor analysis of the ISM-BN model, the list of quality factors that need to be controlled and paid attention to find that these quality factors have the following characteristics and propose corresponding measures: (1) A prefabricated construction project in Nantong City was analyzed using the proposed evaluation model. The analysis results were consistent with similar evaluations, proving the practicality and reasonableness of the model. (2) The design stage had a lower probability of serious quality problems than the other three stages. The important factors were focused on the lack of experience of designers, unreasonable design solutions or links, and design specifications. Increasing the training of design personnel and enhancing their sense of responsibility are essential steps for improving the quality of the design stage. Design organizations should arrange the design plan more reasonably and strengthen the coordination between the prefabricated design and the construction plan to ensure the design project is completed on time. Multiple factors such as functionality, feasibility, economy, and sustainability should be taken into consideration by designers when making design plans to facilitate project success. (3) The probability of serious quality problems in the production stage was significantly higher than that in the design stage, but it was overall slightly lower than that in the transportation and construction stages. The factors leading to production quality problems were mainly focused on the production process's specification and supervision and the raw materials' rationing. To ensure prefabricated components meet production standards, production enterprises should introduce information technology management systems such as BIM to better tailor for the specific needs of the prefabrication process, which can offer effective inventory management, quality control, and precise progress management. In addition, standardized raw material ratios and component maintenance systems should be established, which can provide accurate maintenance records (e.g., time and personnel) to ensure the traceability and consistency of maintenance work. (4) The probability of serious quality problems in the transportation stage was slightly lower than in the construction stage. The factors leading to transportation quality problems were mainly focused on the lack of professionalism and responsibility of transportation personnel. For the transportation stage, transportation companies should strengthen the training of transportation personnel to ensure they can reasonably arrange component transportation plans. Modern technologies such as GPS and vehicle diagnostic systems should be adopted to ensure the transparency of the transportation process, which can significantly improve transportation efficiency by optimizing route planning and ensuring the safe and on-time arrival of the components. (5) The construction stage was the most critical stage of a project. The probability of quality problems in this stage was significantly higher than in the other three stages. The factors leading to construction quality problems were mainly focused on the staff's responsibility, the plan's rationality, and the components' quality. Therefore, a responsibility system should be established to urge workers to take their work seriously. For instance, quality supervision personnel should be appointed to conduct regular inspections and evaluations to implement quality monitoring in the construction stage. Reasonable construction plans should be formulated to ensure the construction process proceeds smoothly. Prefabricated components should be inspected strictly according to the requirements of the drawings to reduce deviations caused by component issues during the construction stage.

This paper had additional difficulties to solve: (1) The acquisition of quality factors for prefabricated buildings was mainly obtained through literature research and expert interviews. More scientific methods can be explored to revise and supplement the indicators, such as case study method, brainstorming method, field investigation method, etc. (2) The final stage involved in the index of factors affecting prefabricated building quality established in this paper was the construction stage. The operation and maintenance stages after completion have not been involved. The operation and maintenance stage involves the maintenance of prefabricated buildings and the actual interests of the owners. Future research can focus on screening and supplementing the factor indicators affecting quality at this stage.

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Appendix A

Table A1. Quality Factor Questionnaire.

Stage	Quality Factors	Experts Add
Design stage	Lack of precast design skills or experience Insufficient responsibility of designers Inadequate communication and coordination among professional designers Insufficient communication between designers and other stakeholders Design standardization is not high Lack of coordination between prefabricated design and construction plan Design time is tight	
Prefabricated component production stage	Relevant staff have weak quality awareness Insufficient professional competence of production personnel Production equipment does not meet the standard The curing conditions do not meet the requirements (standard curing room conditions) Lack of technical specifications and standards for component production Lack of production quality management information system The production process cannot meet the quality requirements Components not stored according to standard (industry standard) Workshop temperature and humidity do not meet the requirements Production time is tight	
Transport stage	Transport personnel are not professional enough Insufficient sense of responsibility of transport personnel Unreasonable selection of transport tools Unreasonable selection of hoisting tools Unreasonable transportation route planning Improper loading and unloading of prefabricated components Prefabricated components transportation protection measures are not in place The transportation distance is too long	
Construction stage	Insufficient practical experience of construction workers and managers Insufficient sense of responsibility of construction personnel Insufficient quality and level of supervisors Prefabricated components are checked careless Insufficient connection strength of prefabricated components (e.g., insufficient grouting strength, insufficient bolt strength) Lack of construction quality inspection tools Instructions for on-site assembly and construction are not detailed or accurate Unreasonable construction schedule Improper construction practices Improper stacking of prefabricated components Construction workers lack reasonable working surfaces	

Table A2. Influence relationships in the design stage.

Quality Factors	Number	Direct Influencing Factors
Lack of precast design skills or experience	D1	
Insufficient responsibility of designers	D2	
Inadequate communication and coordination among professional designers	D3	
Insufficient communication between designers and other stakeholders	D4	
Split design is unreasonable or not in place	D5	
Design standardization is not high	D6	
Lack of coordination between traditional design and prefabricated design	D7	
Lack of coordination between prefabricated design and construction plan	D8	
Design time is tight	D9	

Table A3. Scores of factors affecting the quality of prefabricated buildings.

Score	1	2	3	4	5
Probability of occurrence Degree of impact	Hardly happens Almost no effect	Rarely occurs Less affected	Generally Generally	More frequent More serious	Happens frequently Seriously affected

Table A4. Sample Questionnaire in the design stage.

Score / Risk Factors	Degree of Loss					Probability of Occurrence				
	1	2	3	4	5	1	2	3	4	5
Lack of precast design skills or experience D1										
Insufficient responsibility of designers D2										
Inadequate communication and coordination among professional designers D3										
Insufficient communication between designers and other stakeholders D4										
Split design is unreasonable or not in place D5										
Design standardization is not high D6										
Lack of coordination between traditional design and prefabricated design D7										
Lack of coordination between prefabricated design and construction plan D8										
Design time is tight D9										

Table A5. Sample Questionnaire in the production stage.

Score / Risk Factors	Degree of Loss					Probability of Occurrence				
	1	2	3	4	5	1	2	3	4	5
Relevant staff have weak quality awareness P1										
Insufficient professional competence of production personnel P2										
Insufficient quantity of raw materials (such as steel bars, cement not in the prescribed quantity) P3										
Production equipment does not meet the standard P4										

Table A5. *Cont.*

Score / Risk Factors	Degree of Loss					Probability of Occurrence				
	1	2	3	4	5	1	2	3	4	5
The curing conditions do not meet the requirements (standard curing room conditions) P5										
Unreasonable ratio of raw materials P6										
Lack of technical specifications and standards for component production P7										
Lack of production quality management information system P8										
The production process cannot meet the quality requirements P9										
Components not stored according to standard (industry standard) P10										
Workshop temperature and humidity do not meet the requirements P11										
Production time is tight P12										

Table A6. Sample Questionnaire in the transportation stage.

Score / Risk Factors	Degree of Loss					Probability of Occurrence				
	1	2	3	4	5	1	2	3	4	5
Transport personnel are not professional enough T1										
Insufficient sense of responsibility of transport personnel T2										
Unreasonable selection of transport tools T3										
Unreasonable selection of hoisting tools T4										
Unreasonable shipping sequence of prefabricated components T5										
Unreasonable transportation route planning T6										
Improper loading and unloading of prefabricated components T7										
Prefabricated components transportation protection measures are not in place T8										
The transportation distance is too long T9										

Table A7. Sample Questionnaire in the construction stage.

Score / Risk Factors	Degree of Loss					Probability of Occurrence				
	1	2	3	4	5	1	2	3	4	5
Insufficient practical experience of construction workers and managers C1										
Insufficient sense of responsibility of construction personnel C2										
Inadequate communication between various units and on-site construction personnel C3										
Insufficient quality and level of supervisors C4										
Prefabricated components are checked careless C5										

Table A7. *Cont.*

Score / Risk Factors	Degree of Loss					Probability of Occurrence				
	1	2	3	4	5	1	2	3	4	5
Insufficient connection strength of prefabricated components (e.g., insufficient grouting strength, insufficient bolt strength) C6										
Lack of construction quality inspection tools C7										
Instructions for on-site assembly and construction are not detailed or accurate C8										
Unreasonable construction schedule C9										
Improper construction practices C10										
Component installation accuracy is not enough C11										
Improper stacking of prefabricated components C12										
Construction workers lack reasonable working surfaces C13										

Table A8. Reachability matrix in the production stage.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
P1	1	0	1	0	0	1	0	0	0	1	0	0
P2	0	1	0	0	0	0	0	0	1	0	0	0
P3	0	0	1	0	0	1	0	0	0	0	0	0
P4	0	0	0	1	0	0	0	0	1	0	0	0
P5	0	0	0	0	1	0	0	0	0	0	0	0
P6	0	0	0	0	0	1	0	0	0	0	0	0
P7	0	0	0	1	1	0	1	0	1	0	0	0
P8	0	0	1	0	0	1	0	1	1	1	1	0
P9	0	0	0	0	0	0	0	0	1	0	0	0
P10	0	0	0	0	0	0	0	0	0	1	0	0
P11	0	0	0	0	0	0	0	0	1	0	1	0
P12	0	0	0	0	0	0	0	0	1	0	0	1

Table A9. Reachability matrix in the transportation stage.

	T1	T2	T3	T4	T5	T6	T7	T8	T9
T1	1	0	1	1	1	1	1	0	1
T2	0	1	0	1	1	0	1	1	0
T3	0	0	1	0	0	0	0	0	0
T4	0	0	0	1	1	0	1	0	0
T5	0	0	0	0	1	0	1	0	0
T6	0	0	0	0	0	1	0	0	1
T7	0	0	0	0	0	0	1	0	0
T8	0	0	0	0	0	0	0	1	0
T9	0	0	0	0	0	0	0	0	1

Table A10. Reachability matrix in the construction stage.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
C1	1	0	0	0	0	1	0	0	1	1	1	0	1
C2	0	1	0	0	1	1	0	0	0	0	0	1	0
C3	0	0	1	0	0	0	0	0	1	0	0	0	1
C4	0	0	0	1	0	1	0	0	0	0	1	0	0
C5	0	0	0	0	1	0	0	0	0	0	0	0	0
C6	0	0	0	0	0	1	0	0	0	0	0	0	0
C7	0	0	0	0	0	1	1	0	0	0	1	0	0

Table A10. *Cont.*

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
C8	0	0	0	0	0	1	0	1	0	0	1	1	0
C9	0	0	0	0	0	0	0	0	1	0	0	0	1
C10	0	0	0	0	0	1	0	0	0	1	1	0	0
C11	0	0	0	0	0	0	0	0	0	0	1	0	0
C12	0	0	0	0	0	0	0	0	0	0	0	1	0
C13	0	0	0	0	0	0	0	0	0	0	0	0	1

Appendix B

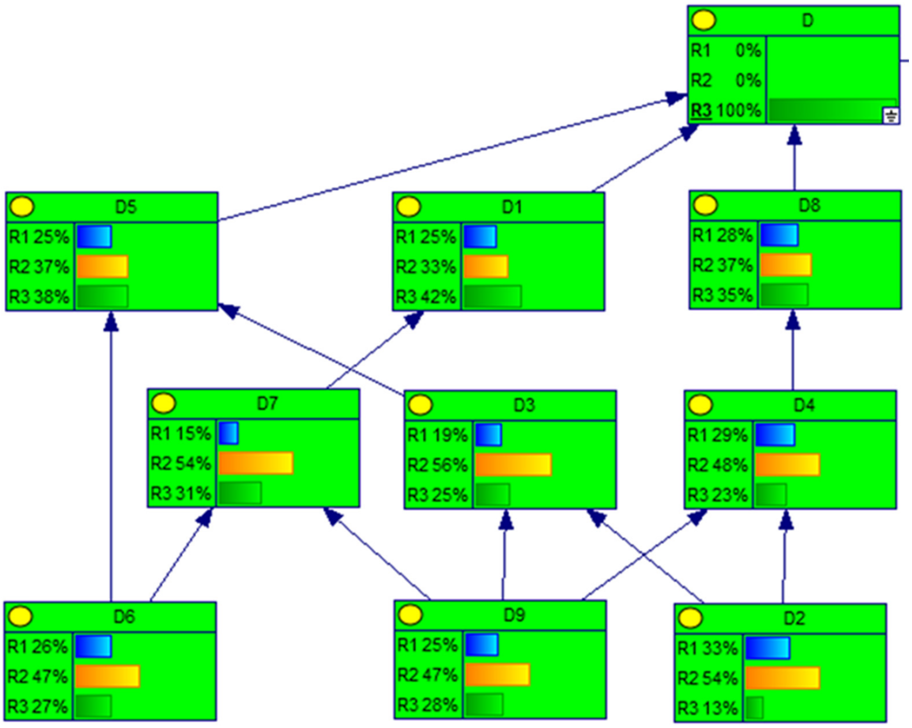

Figure A1. Posterior probability of design stage.

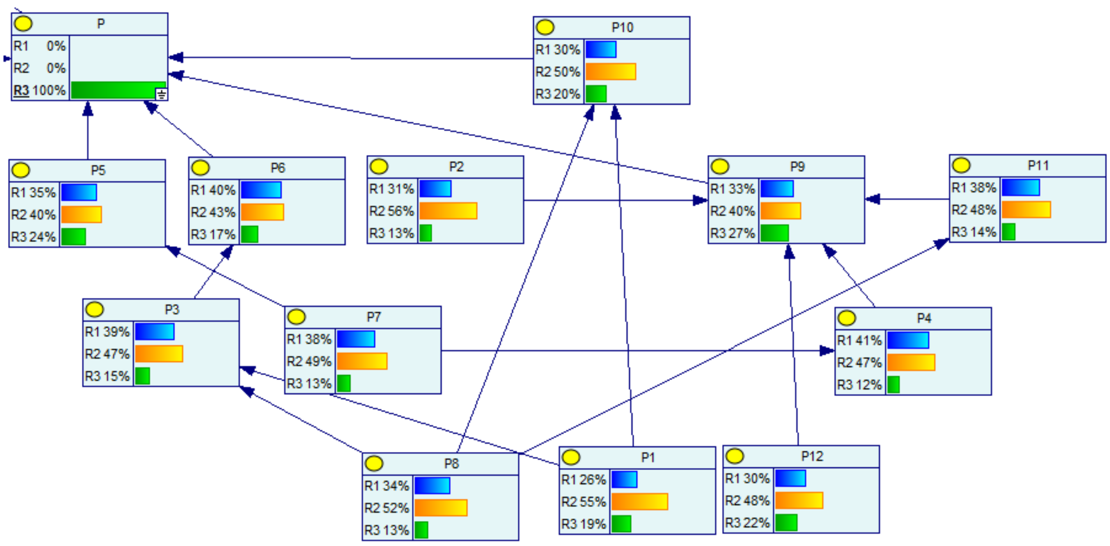

Figure A2. Posterior probability of production stage.

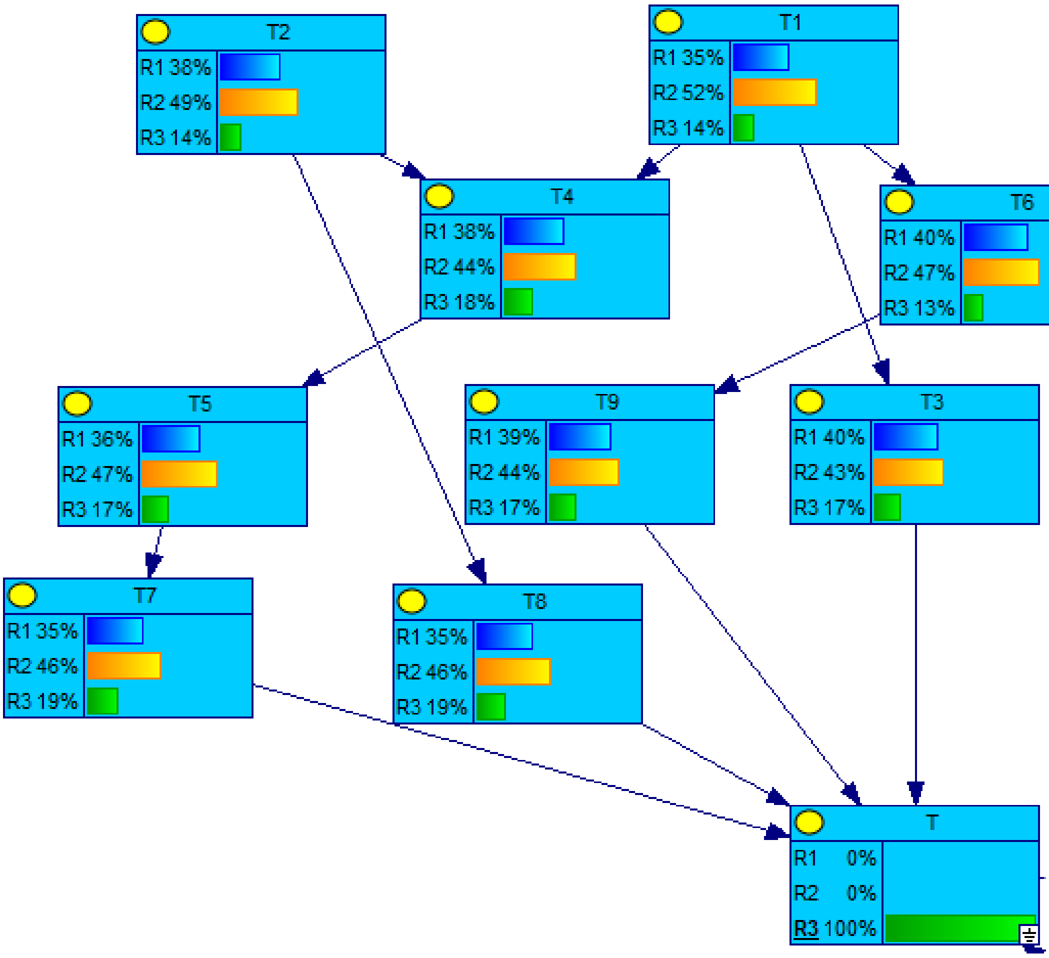

Figure A3. Posterior probability of transport stage.

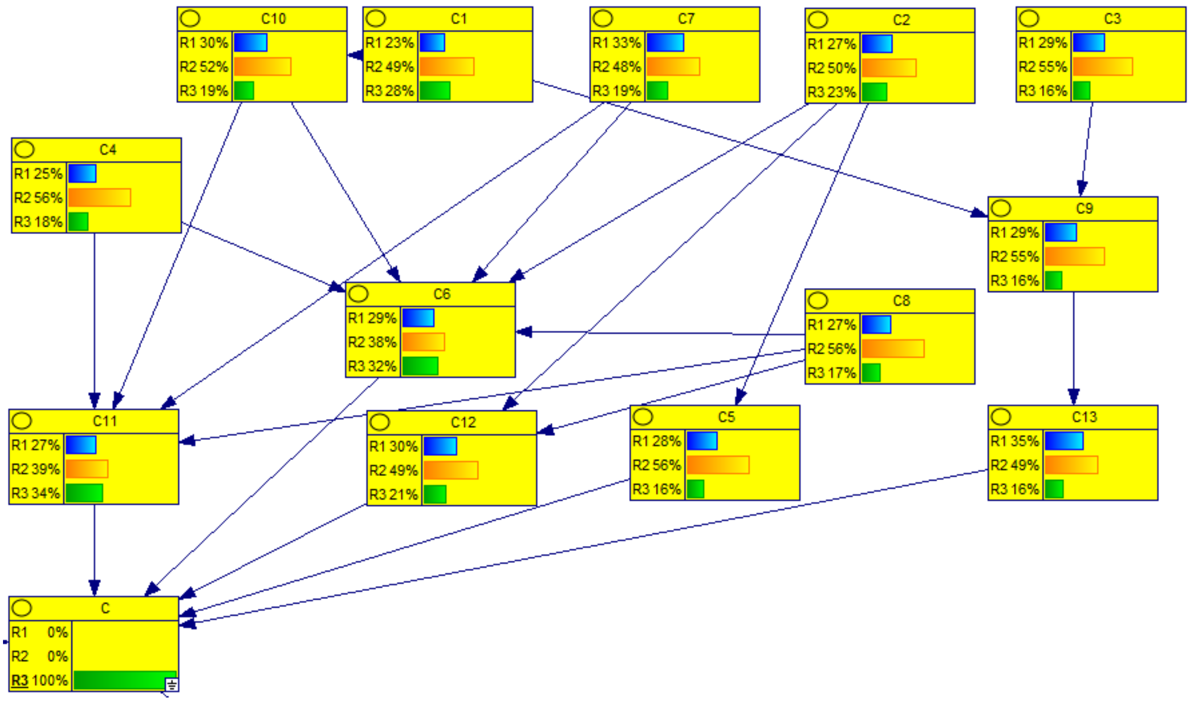

Figure A4. Posterior probability of construction stage.

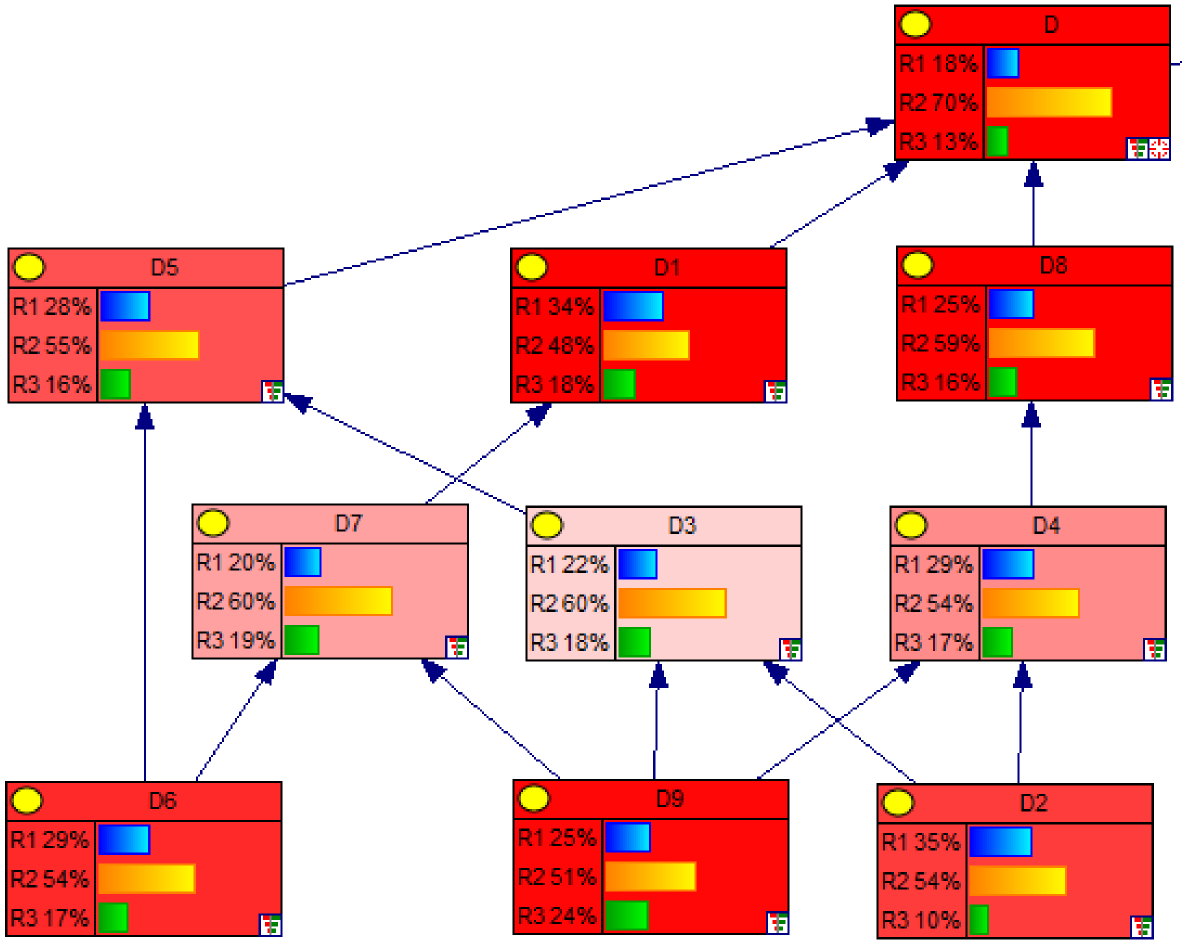

Figure A5. Sensitivity analysis model in the design stage.

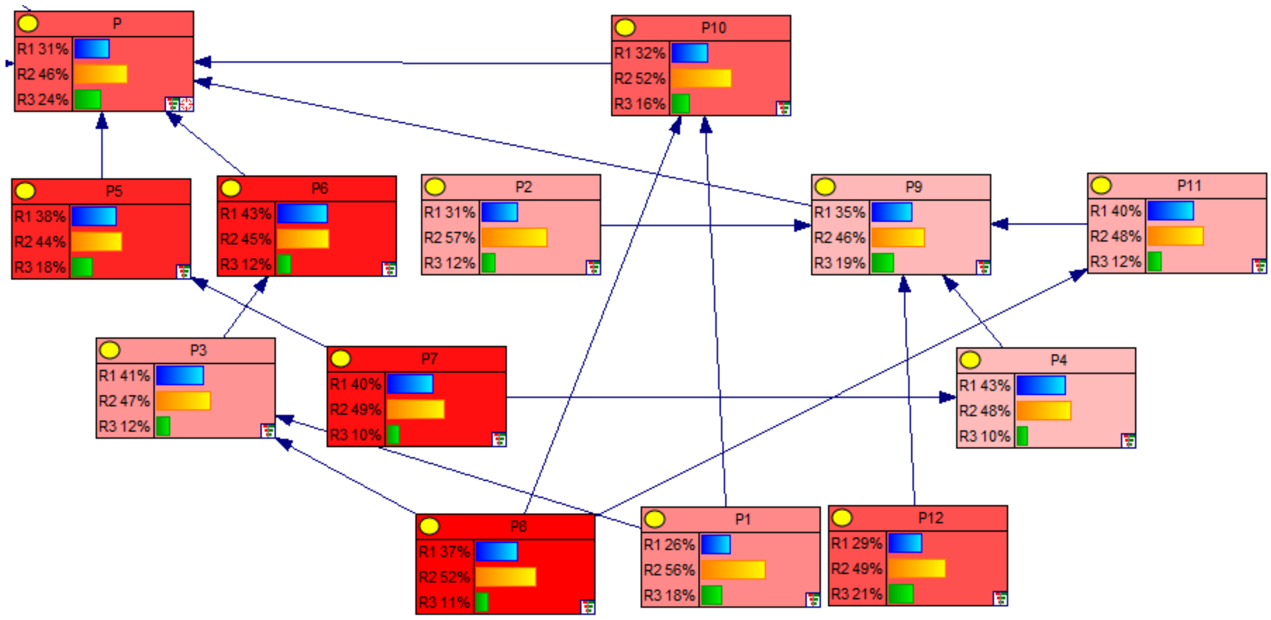

Figure A6. Sensitivity analysis model in the prefabricated components production stage.

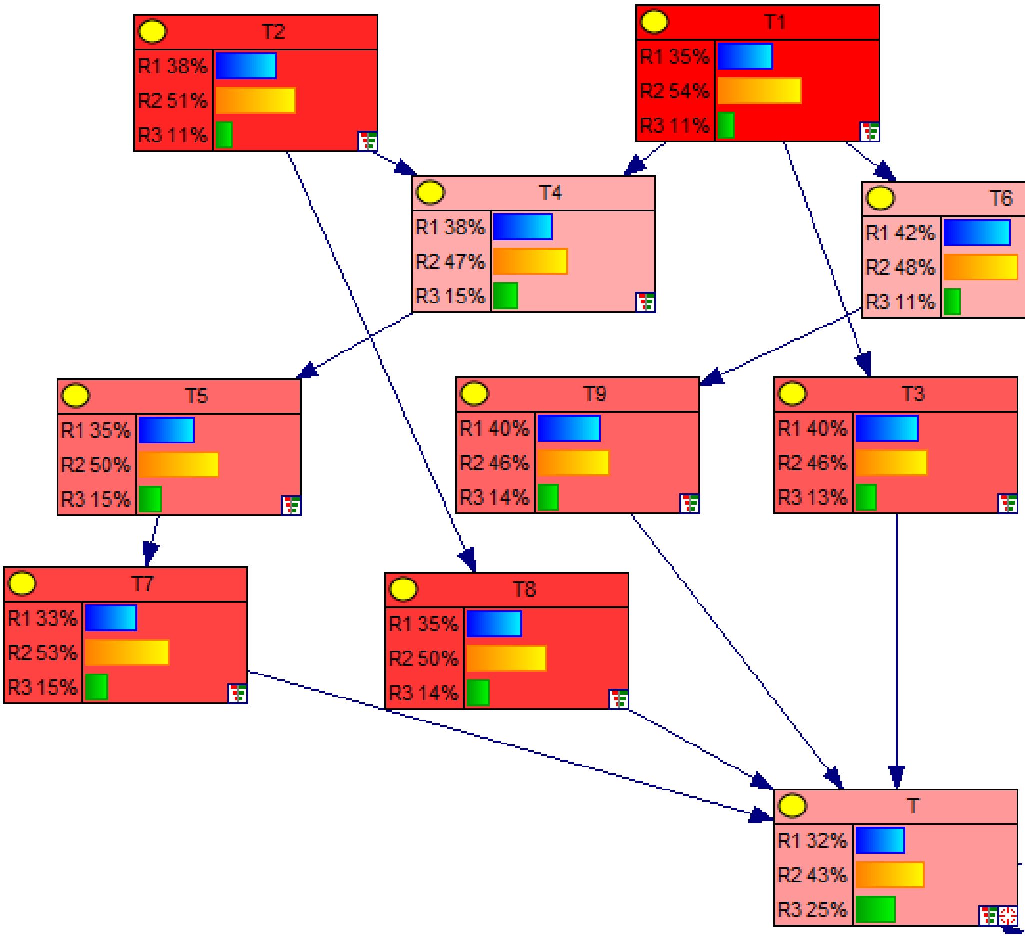

Figure A7. Sensitivity analysis model in the transportation stage.

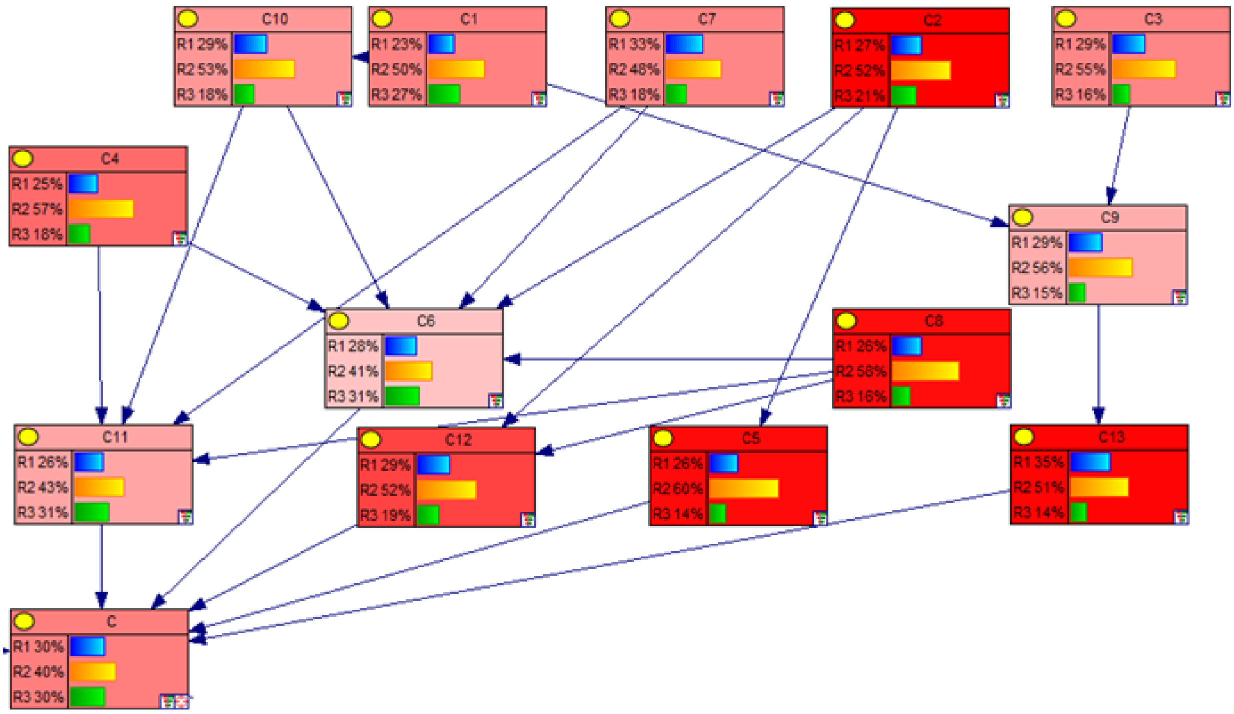

Figure A8. Sensitivity analysis model in the construction stage.

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