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Schedule Risk Evaluation and Control Countermeasures for Supporting Infrastructure Projects of Large-Scale Equipment based on ISM-BN

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Abstract

To address the issues of vague schedule risk identification, insufficient quantitative research, and poorly targeted control measures in supporting infrastructure projects for large-scale equipment, this paper takes the perspective of the owner (the construction unit) as the starting point. Through expert interviews, a set of risk factors for such projects is identified and established. Using Interpretive Structural Modeling (ISM), the hierarchical relationships and propagation paths of schedule risks are revealed. A Bayesian Network (BN) model is then constructed for quantitative analysis to identify key risk nodes and causal chains, and to determine and classify schedule risk levels. Based on a comprehensive evaluation, targeted risk control measures are proposed, providing a reference for the owner's schedule management.

Keywords

Large-scale Equipment Supporting Infrastructure Projects; Owner's Perspective; Schedule Risk Control; ISM-BN.

1. Research Background

With the rapid development of the national defense and military industry, the construction demands for large-scale equipment supporting infrastructure projects [1-2] are becoming increasingly urgent. The owner (the construction unit), as the main body of project investment and overall coordination, plays a central role in schedule risk management. However, existing research largely focuses on the contractor's perspective, lacking consideration of overall project control. As a result, schedule risk identification remains vague, quantitative analysis is insufficient, and control measures are poorly targeted. To address these issues, this paper, from the owner's perspective, proposes a schedule risk evaluation and control countermeasure system for large-scale equipment supporting infrastructure projects based on ISM-BN, offering new ideas and solutions for the schedule control of such projects.

2. Relevant Concepts

Supporting infrastructure projects for large-scale equipment (such as large radars, optical telescopes, and communication equipment) are infrastructure projects that provide physical support for the operation of such equipment. The owner's perspective, distinct from the purely contractor's perspective[3-5], highlights the overall viewpoint of the construction unit as the leading party. It involves a full-process, multi-entity analysis of the factors influencing project schedule arising from each link in the contract performance of all participating units - including surveying, design, construction, and supervision - during the project implementation.

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3. Identification of Schedule Risk Factors from the Owner's Perspective

Due to their large land footprint, high equipment power, and poor environmental friendliness, large-scale equipment supporting infrastructure projects are usually deployed in remote areas, resulting in weak social support and pronounced resource constraints. Through interviews with two owner representatives with more than 8 years of experience in managing similar projects, two project managers with more than 5 years of experience in construction management of large-scale equipment supporting projects, and one project leader from the design unit, it was ultimately determined that the risk set for such projects primarily consists of 6 categories and 19 factors.

Table 1. Risk Factor Set of Large-scale Equipment Supporting Infrastructure Projects

Risk Factor Categorye	Risk Factor
Natural Environment Factors A	A1 - Severe weather
	A2 - Natural disasters such as landslides
	A3 - Remote location with poor construction support conditions
Organization and Management Factors B	B1 - Unscientific construction organization design
	B2 - Delayed payment of project funds by the construction unit
	B3 - Slow approval of change orders and certifications
	B4 - Poor interface between infrastructure construction and equipment installation processes
	B5 - Rework due to substandard construction quality
Social Environment Factor C	C - Lengthy approval procedure cycle
Technical Factors D	D1 - Numerous errors and omissions in construction drawings
	D2 - Discrepancy between geological conditions and survey documents
	D3 - Slow determination of equipment-related technical parameters
	D4 - Material technical parameters not in compliance with contract
Personnel Factors E	E1 - Insufficient professional competence of the design unit
	E2 - Inadequate organizational and management capabilities of the contractor's project management team
	E3 - Lack of experience in specialized subcontracting teams
Resource Factors F	F1 - Untimely supply of materials and equipment
	F2 - Insufficient number of laborers
	F3 - Shortage of construction machinery

4. ISM-Based Analysis of Risk Hierarchical Structure

Interpretive Structural Modeling (ISM)[6-8] is a method for complex system analysis. By constructing the adjacency matrix and reachability matrix among factors, it transforms vague elements into a multi-level hierarchical directed structure, clearly revealing the hierarchical and influential relationships among factors. This paper takes the 19 schedule risk factors as system elements and adopts the Delphi method to invite domain experts to judge the direct influence relationships between factors. The specific steps for constructing the ISM model are as follows:

(1) Construct the adjacency matrix. The 19 schedule risk factors constitute the system element set. Through expert judgment, the direct influence relationship between any two factors is determined. If factor S_i has a direct influence on S_j, it is assigned a value of 1; otherwise, it is assigned 0. The diagonal elements represent self-influence and are uniformly set to 0, thus forming a 19-order adjacency matrix.

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(2) Calculate the reachability matrix M. Add the adjacency matrix to the identity matrix of the same order, and then perform power operations based on Boolean operation rules until the matrix result remains unchanged. This yields the reachability matrix, which comprehensively reflects all direct and indirect influence relationships among the factors.

(3) Partition the risk factor levels. Based on the reachability matrix, determine the reachability set and antecedent set for each factor. Using the condition that the reachability set equals the intersection, extract and partition the risk factors into levels, thereby clarifying the hierarchical position of each factor in the system.

(4) Construct the hierarchical structure model. Based on the level partitioning results, draw a multi-level hierarchical directed graph to clarify the propagation paths and functional relationships of the risk factors, distinguishing direct surface risks, intermediate indirect risks, and deep root risks. This provides a direct basis for the subsequent construction of the Bayesian Network (BN) topology.

After calculation, the 19 schedule risk factors are divided into three levels:

Level 1 (Surface direct risks): A2, B3, B4, B5, C, D2, F1, F2, F3;

Level 2 (Intermediate indirect risks): A1, A3, B1, B2, D1, D3, D4, E3;

Level 3 (Deep root risks): E1, E2.

5. BN-Based Risk Factor Analysis

5.1. Bayesian Network Model Construction

Based on the hierarchical risk relationships and propagation paths obtained from Interpretive Structural Modeling (ISM), a Bayesian Network (BN) [9-11] for schedule risks of large-scale equipment supporting infrastructure projects is constructed. Specifically, the directed edges in the ISM hierarchical structure diagram are directly transformed into directed arcs in the BN, with nodes corresponding to each risk factor and the project delay target, forming the initial network topology. To reduce the complexity of Conditional Probability Tables (CPTs) and facilitate expert probability assessment, binary discrete variables are adopted in this model, with all nodes uniformly set to two states:“Yes”(occurrence) and“No”(non-occurrence).

(1) Prior probability determination

The prior probabilities of root nodes are determined based on expert surveys and project experience.

(2) Conditional Probability Table (CPT) specification

Based on the direct influence relationships among factors determined by ISM and combined with engineering experts’experience, the CPTs for non-root nodes are constructed. The specification follows these principles:①CPTs are constructed only for node pairs with direct directed edges; root nodes without parent nodes only require the definition of prior probabilities.②When a parent node occurs, the probability of the child node occurring is significantly higher than when the parent node does not occur, reflecting the amplification effect of risk along the propagation path.③Under the joint action of multiple parent nodes, the probability of the child node occurring is not lower than that under the action of any single parent node, reflecting the accumulation and coupling characteristics of risk factors.④The sum of the probabilities of all states of a child node equals 1. The specific probability values are determined through a combination of expert interviews and historical project data.

5.2. Bayesian Network Inference Analysis

Based on the constructed Bayesian Network model, forward probability inference, backward diagnostic inference, and sensitivity analysis are conducted to identify key causative factors and maximum causal chains, thereby achieving a quantitative assessment of schedule risk.

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(1) Forward probability inference and overall risk assessment

Without setting any evidence, forward inference is performed using the Bayesian Network to calculate the unconditional probability of each node. As shown in Fig. 1, the unconditional probability of the“project delay”node is 46%, indicating that the overall schedule risk of this large-scale equipment supporting infrastructure project is at a medium-to-high level. This also illustrates, to a certain extent, the practical necessity of studying the schedule risk management of such projects.

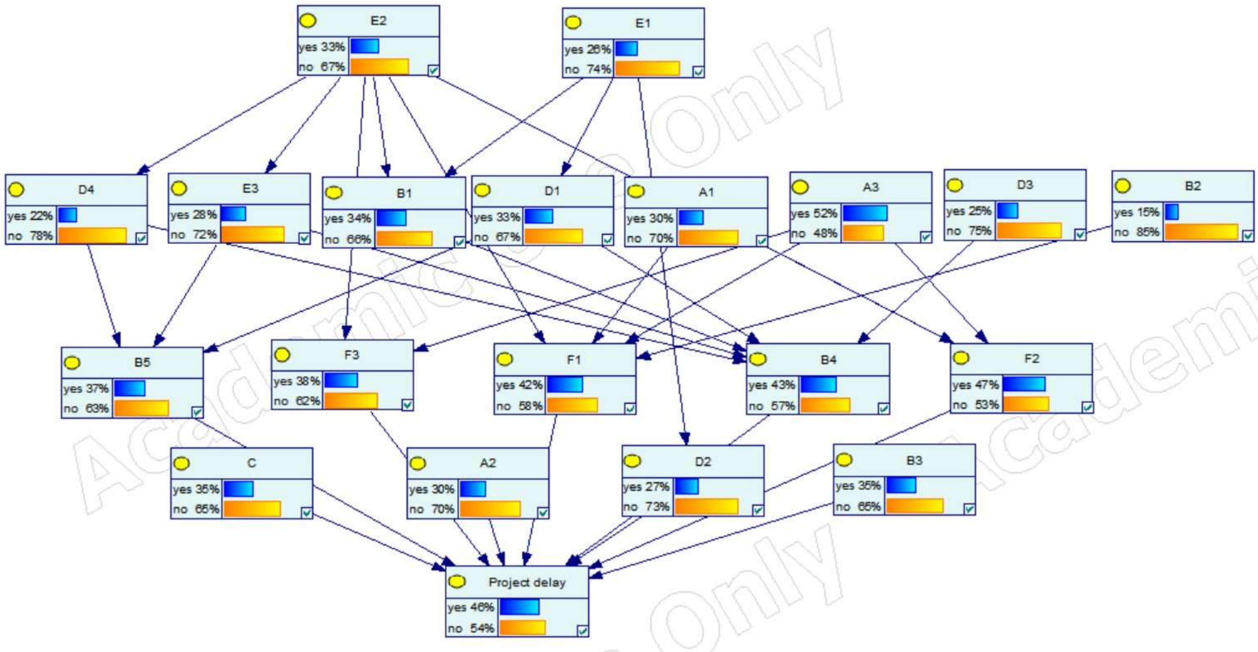

Fig. 1 Bayesian Network Parameter Learning Results

(2) Backward diagnostic inference and identification of maximum causal chains

As shown in Fig. 2, the target node“project delay”is set to a high-risk state (100%). After running the inference, the posterior probabilities of each risk factor node are calculated, and the increase relative to their prior probabilities is determined. The factors are sorted in descending order of the increase, and the top five are taken as the key causes of project delay, in order: shortage of construction machinery, rework due to substandard quality, untimely supply of materials, lengthy approval cycle, and natural disasters. The overall increase is relatively limited.

Combined with the ISM multi-level hierarchical structure, the paths with the greatest probability contributions and the most significant propagation relationships are extracted, and three core maximum causal chains are identified:①(Insufficient capability of the contracting enterprise/Poor support conditions)-Shortage of construction machinery-Project delay;②(Material/equipment parameter discrepancy/Lack of experience in specialized subcontracting teams)-Rework due to substandard quality-Project delay;③(Insufficient capability of the contracting enterprise/Severe weather/Poor remote support conditions/Untimely disbursement of project funds) -Untimely supply of materials -Project delay.

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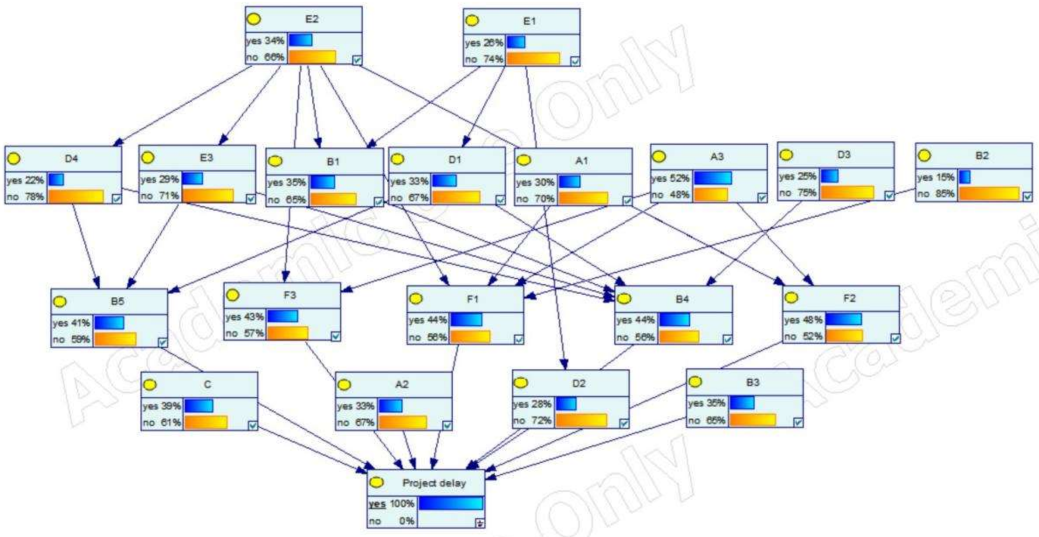

Fig. 2 Results of Bayesian Network Backward Inference

(3) Sensitivity analysis and verification of key causes

This study employs GeNIe software to conduct sensitivity analysis. During the analysis, the Parameter Spread is set to 10% to evaluate the local impact of small variations in each risk factor on the probability of project schedule delay. This choice, referring to the recommended values in the official GeNIe documentation, aims to identify the leverage factors that are most sensitive to the model output.

As shown in Fig. 3, "lengthy approval cycle," "natural disasters," and "rework due to substandard quality" are the three factors with the highest sensitivity. Even with a 10% parameter spread (i.e., small fluctuations of 10% in parameters), they can cause a significant chain reaction on the probability of schedule delay. This indicates that these three risk links are relatively sensitive to the entire project schedule system, and greater monitoring and prevention efforts are needed in management practice.

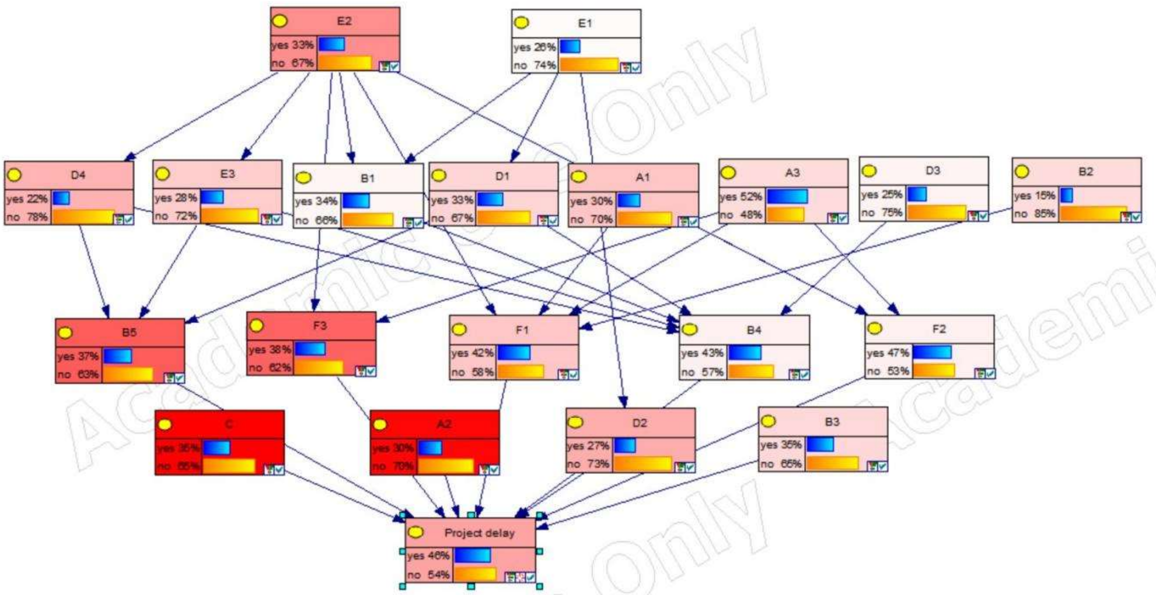

Fig. 3 Results of Bayesian Network Sensitivity Analysis

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5.3. Risk Level Classification and Evaluation Result Analysis

Based on the Bayesian Network analysis results, the schedule risk level determination criteria for large-scale equipment supporting infrastructure projects are established, the 19 risk factors are classified, and a comprehensive evaluation is conducted.

(1) Risk level classification criteria

To systematically identify and differentiate the degree of influence of various risk factors on the schedule of large-scale equipment supporting infrastructure projects, a three-dimensional comprehensive judgment principle of"Basic Risk Level–Key Causal Intensity–High-Leverage Sensitivity"is adopted, integrating the results of forward inference, backward inference, and sensitivity analysis of the Bayesian Network. The risk factors are divided into three levels: high, medium, and low.

High Risk: Meeting one or more of the following conditions simultaneously:①High marginal probability in forward inference (usually >45%);②Significant increase in posterior probability after backward inference;③Ranking at the forefront in sensitivity analysis (most sensitive to schedule delay impact). Such factors lie at the core of the maximum causal chains and require priority control.

Medium Risk:Possessing a certain base occurrence probability (30%–45%), or a moderate increase in backward inference, or average performance in sensitivity analysis, but playing an intermediate transmission role in risk propagation, with an identifiable impact on the overall schedule.

Low Risk:Possessing a certain base occurrence probability (<30%), a negligible increase in backward inference, and ranking low in sensitivity analysis. Such factors can be effectively avoided through routine management measures without requiring excessive resource input.

(2) Risk factor level classification results

According to the above criteria, the 19 schedule risk factors are classified, and the results are shown in Table 2.

Table 2. Classification Results of Project Schedule Risk Factor Levels

Risk Level	Risk Factors	Quantity
High Risk	F3, B5, F1, C, A2, A3, F2	7 items
Medium Risk	E2, B1, D1, A1, B4, B3	6 items
Low Risk	E1, D4, E3, D3, B2, D2	6 items

6. Conclusion

By integrating the aforementioned ISM hierarchical structure, Bayesian Network inference analysis, and risk factor level classification, the most probable schedule delay paths for large-scale equipment supporting infrastructure projects are identified as follows:

(1)Due to the insufficient capability of the contracting enterprise, limited resource mobilization capacity, and poor support conditions in remote project locations, a shortage of large key construction machinery occurs, leading to project delays.

(2) Because the materials and equipment procured by the contracting enterprise have parameters that do not conform to contract or drawing requirements, or the specialized subcontracting team lacks experience, construction quality is substandard or process acceptance fails, and rework causes schedule delays.

(3) During the construction period, severe weather such as typhoons and persistent rain/snow, coupled with the remote location and poor local support, as well as the contracting enterprise's

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limited resource mobilization ability, result in serious delays in the arrival of certain key materials on site, thereby causing project delays.

From the owner's perspective (the construction unit), the following targeted measures can be taken:

(1)Select high-quality contracting enterprises. The delay causes indicate that the contracting enterprise (construction contractor), as the main implementing entity of the project, plays a critical role; its own capability and strength are closely related to resource mobilization efficiency in remote areas, risk anticipation and response capacity, and the ability to deploy long-term cooperative specialized teams — all of which are highly relevant to schedule risk control. To address this, the owner should, at the very beginning of the project (the tendering stage), adopt a comprehensive evaluation method rather than the reasonable lowest price method to select construction enterprises with strong capabilities and good reputations.

(2) Focus on material and equipment selection. As the leading party of the project, the owner should pay close attention to the selection of materials and equipment, coordinate with the supervision unit and design unit, and, in line with the project schedule, pre-verify the brands, specifications, and models of important materials and equipment with all participating parties, and obtain timely confirmation through joint signature. Sufficient time should be reserved for procurement, production, and transportation to ensure that the arrival of important materials and equipment meets the construction schedule requirements.

(3) Strengthen construction quality control. The owner should reinforce its supervisory responsibility, urge the construction contractor to select high-quality subcontracting teams, rigorously conduct technical disclosure, and clarify process requirements to ensure that schedule is not affected by rework due to substandard quality.

(4) Make thorough emergency preparations. Since most of these projects are located in remote areas with frequent severe weather, natural disasters, and local microclimates, the owner (construction unit) should urge the construction contractor to develop targeted emergency plans and conduct drills, pre-stock relevant emergency supplies, and, when formulating the schedule, reserve reasonable buffer time to prevent force majeure from affecting the achievement of schedule targets and delaying equipment installation.

(5) Improve the owner's approval efficiency. In processes such as change order confirmation, material selection and sample finalization, and disbursement of project funds, the construction unit should establish working mechanisms and specify approval time limits for relevant matters to eliminate schedule delays caused by bureaucratic obstacles in the owner's approval procedures.

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