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FUZZY COMPREHENSIVE RISK EVALUATION OF CHINA'S METRO TRANSPORTATION PUBLIC-PRIVATE PARTNERSHIP PROJECTS

Jinghan YU[1,*], Djoen San SANTOSO[1]

[1] Department of Civil and Infrastructure Engineering, School of Engineering and Technology, Asian Institute of Technology, Pathumthani, Thailand.
[*] corresponding author: st121693@ait.ac.th

Abstract

The Public-Private Partnership (PPP) model has been widely adopted in China's metro infrastructure to enhance resource allocation efficiency. However, PPP projects have a long life cycle and diverse risk factors, and effective risk assessment is thereby essential to achieve project success. This study develops a fuzzy comprehensive risk evaluation model by integrating the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation methods. A comprehensive risk indicator set consisting of 11 dimensions and 45 indicators is established, and AHP method is applied to calculate indicators importance weights. Subsequently, the weights are combined with fuzzy mathematical theory to quantitatively assess the risk levels by calculating the risk level scores. Then, by applying this model to the Tianjin Metro Line 7 Phase 1 project, the study identifies that political, construction phase, financing phase, economic, and legal risks as the five key risk indicators, while external and social risks are found to be less significant. The overall project risk level is assessed as above-moderate. Moreover, expert interpretation is conducted to discuss results and propose risk management strategies for key risk indicators. This study validates the fuzzy comprehensive risk evaluation model through case application, provides practical reference for risk management in PPP metro projects.

Keywords:

Public-Private Partnership (PPP);
Metro Transportation;
China;
Quantitative Risk Evaluation;
Analytic Hierarchy Process (AHP);
Fuzzy Comprehensive;
Evaluation.

1 Introduction

The 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China emphasizes accelerating the development of a robust transportation network, the vigorous expansion of urban rail transit, and the formation of new urban clusters to promote urbanization [1]. This is of great significance for improving urban transport networks and strengthening economic and regional exchanges. However, the investment in the construction of urban rail transport is huge, and the operating cost can be up to several times the construction investment [2,3]. Consequently, the government faces a dual financial burden of construction investment and operational subsidies, which provides a feasible ground for the implementation of the Public-private partnership (PPP) model in infrastructure sectors such as urban rail transit. According to available data, over 40 cities in China have carried out urban rail transit PPP projects, with the number of projects approaching 100 [4]. As a result, transportation has progressively become the sector with the highest investment in PPP projects in China, with a cumulative investment of RMB 5.23 trillion (US $719.4 billion), representing approximately one-third of the total PPP investment [5].

The PPP model is a multi-stakeholder cooperation framework for public infrastructure and service projects, which is established by government department and private sector [6]. By leveraging the advantages of private sector in technology and management, it can enhance project supply efficiency, generate reasonable returns for social capital, and simultaneously promote governmental function transformation [7]. Since 2014, China's National Development and Reform Commission (NDRC) and Ministry of Finance (MOF) have started to introduce and refine relevant policies and regulations aimed at guiding and facilitating the rapid development of the PPP model [8]. As a mechanism for reforming the delivery of infrastructure and public service projects, the PPP model has effectively encouraged corporate competition, dismantled traditional government monopolies, and lowered entry barriers for the

private sector [9]. However, despite these developments, some Chinese PPP projects continue to face practical challenges, such as low implementation rates and lower participation of privately-owned enterprises (POEs) compared to state-owned enterprises (SOEs) in both construction and operation phases.

This paper constructs a risk evaluation model based on the fuzzy comprehensive evaluation (FCE) method and analytic hierarchy process (AHP) method to achieve a quantitative assessment of the risk levels of China's metro transportation PPP projects (CMTPPs). Moreover, risk management strategies for key risk indicators of CMTPPs are presented with the utilization of diagrams from three perspectives including risk event prevention, control and response. The main research significance and value are summarized as follows: 1) Identify and construct a risk indicator set (RIS) applicable to CMTPPs based on literature review and expert evaluation; 2) Construct a fuzzy comprehensive risk evaluation (FCRE) model by utilizing a combination of the AHP method and the FCE method; 3) Validate the proposed FCRE model through actual project cases to ensure its practicability and validity; 4) Furthermore, the insights on the management strategies of the key risk indicators of CMTPPs from different perspectives of the government and the private sector are provided, which extends the research results as well as provides meaningful references for the related fields.

2 Methodology

2.1 Research Design

This study develops a FCRE model for CMTPPs by combining the AHP and the FCE methods, and a real project case is applied for model validation. Firstly, this paper searches the literature related to the risks of CMTPPs, and after screening, reviews and analyses the relevant literature, based on which the initial risk factors of this study are obtained. Subsequently, the comprehensive list of risk factors is further refined through expert review and validation, and the AHP structure is applied to construct the RIS applicable to CMTPPs. Then, according to the application process of the FCRE model proposed in this paper, the AHP method is used to analyse and calculate the importance weights of the risk indicators. Finally, this study utilizes the fuzzy linguistic comments and corresponding assigned values of the risk levels of the risk indicators to further calculate the risk level scores through combination of the importance weights and the FCE method to realize the quantitative evaluation of the risk levels (as described in Subsection 2.2).

Based on the results of the quantitative analysis (as presented in Section 3.2), this study invites four experienced industry professionals to interpret the risk level of project's risk indicators and overall project through in-depth discussion. In addition, based on the case analysis and interpretation, this study further proposes corresponding risk management strategies and suggestions for key risk indicators of CMTPPs from the perspectives of different participants in PPP in terms of the prevention of risk events, in-process control, and post-event response, with a view to contributing practical references to the relevant fields as presented in Section 4. Accordingly, the flowchart of the research methodology is presented as below in Figure 1.

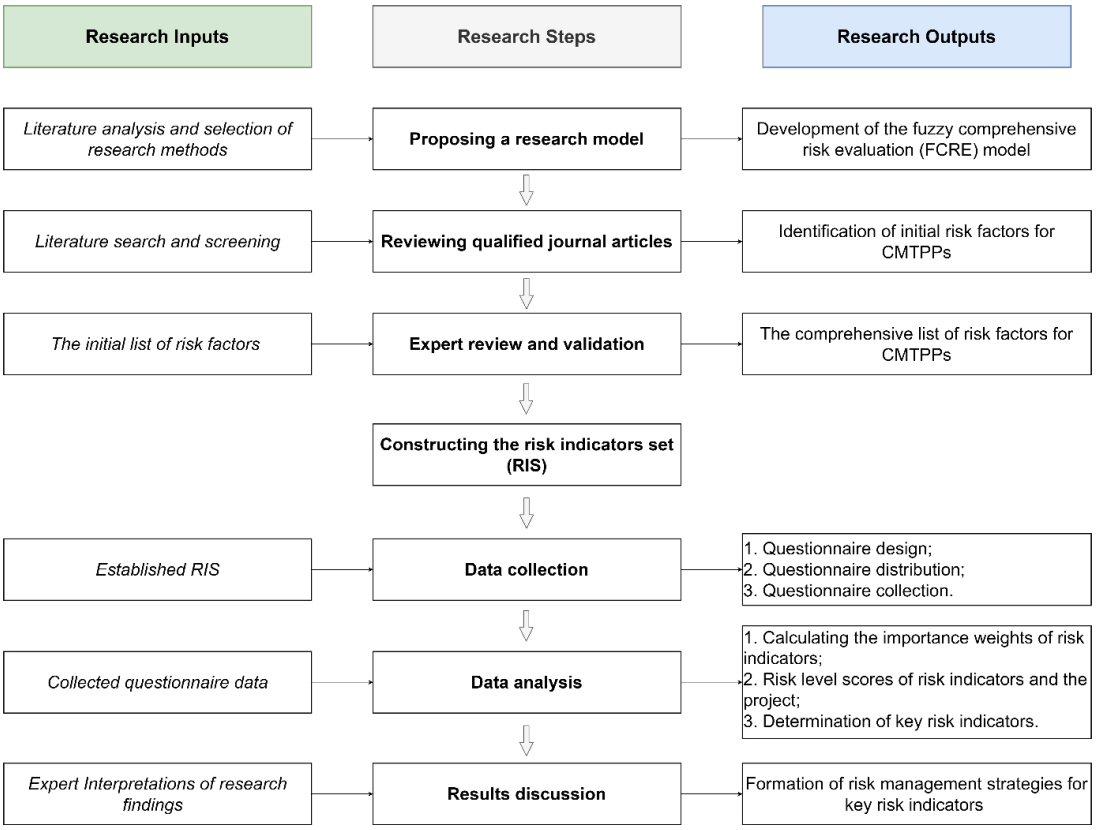

Fig. 1: The flowchart of the research methodology.

2.2 Developing Fuzzy Comprehensive Risk Evaluation Model for CMTPPs

In the process of project risk evaluation, FCE is widely recognized as an effective system evaluation method, which grounded in fuzzy mathematics, leverages fuzzy set theory and membership theory to transform qualitative assessments into quantitative evaluations. It contributes to the realization of dealing with problems that are difficult to describe accurately with numerical values due to information uncertainty, ambiguity, or subjectivity [10]. However, it is important to note that as the number of risk indicators increases, the degree of fuzziness also expands, potentially causing deviations between actual and evaluated results [11].

Based on the theoretical foundation, the FCRE model is developed as shown in Figure 2. Firstly, it starts with the construction of the RIS using the AHP structure, followed by the calculation of the risk indicator importance weights by the AHP method. When there is a failure of the consistency test in the process, it is necessary to return to adjust the judgement matrix of the risk indicators, and when all the indicators satisfy the consistency test criteria, the calculated weights of both the first-level and second-level risk indicators (FRIs and SRIs) can be further integrated with the FCE method.

Subsequently, on the basis of fuzzy set theory and FCE method, the expert's fuzzy linguistic evaluation of the risk indicators is quantitatively analyzed by establishing risk evaluation levels and the corresponding assigned values. After calculating the degree of membership of the indicators, the evaluation matrix of the indicators is constructed, which is then combined with the weights of the indicators calculated by the AHP method to obtain the risk level evaluation scores of the risk indicators as well as the project. The integration of the above methods can achieve a comprehensive assessment of the risk level of CMTPPs, and the application of this model enables a deeper understanding of the level of project risk and facilitates the implementation of appropriate risk management.

Previous studies have also validated the effectiveness of applying FCE methods and models for PPP risk assessment, since the application of FCE method for risk assessment in PPP projects has proven to be an effective method for addressing complex, multi-dimensional risks inherent in such projects. Existing research have highlighted the suitability of FCE for evaluating various types of risks, particularly in infrastructure sectors such as transportation, energy, and environmental projects [12, 13]. For instance, FCE has been employed to assess risks in transport and power infrastructure PPP projects, demonstrating its capacity to quantify and categorize critical risk factors through fuzzy set

theory and non-additive fuzzy integrals, which help stakeholders identify and mitigate risks effectively in the early stages of project development [13]. Similarly, a model based on FCE method has been successfully applied to evaluate the sustainability risks of PPP projects, which incorporates both financial and non-financial risk factors, offering a comprehensive approach to sustainability assessment [14].

Moreover, in the context of China's rapidly developing straw-based power generation sector, FCE method has been used to assess 44 risk factors, providing valuable insights into risk levels and guiding decision-making processes for public and private stakeholders [15]. Additionally, Li and Wang [16] combined FCE with fuzzy analytic hierarchy process (F-AHP) to evaluate the political, economic, and legal risks associated with PPP projects in China' context, the research findings help to offer a tailored risk management framework for the local context. Feng et al. [17] applied FCE to urban rail transit projects, identifying political, legal, and project promotion risks as key contributors to project success, and proposed risk mitigation strategies based on the evaluation results. Furthermore, the results of a comparative study of various multi-attribute decision-making methods conducted by Valipour et al. [18] has confirmed that FCE remains a robust and reliable tool for PPP project risk assessment, offering consistent and actionable insights. These findings underscore the adaptability and effectiveness of fuzzy comprehensive evaluation models in managing PPP project risks, particularly in dynamic and complex environments.

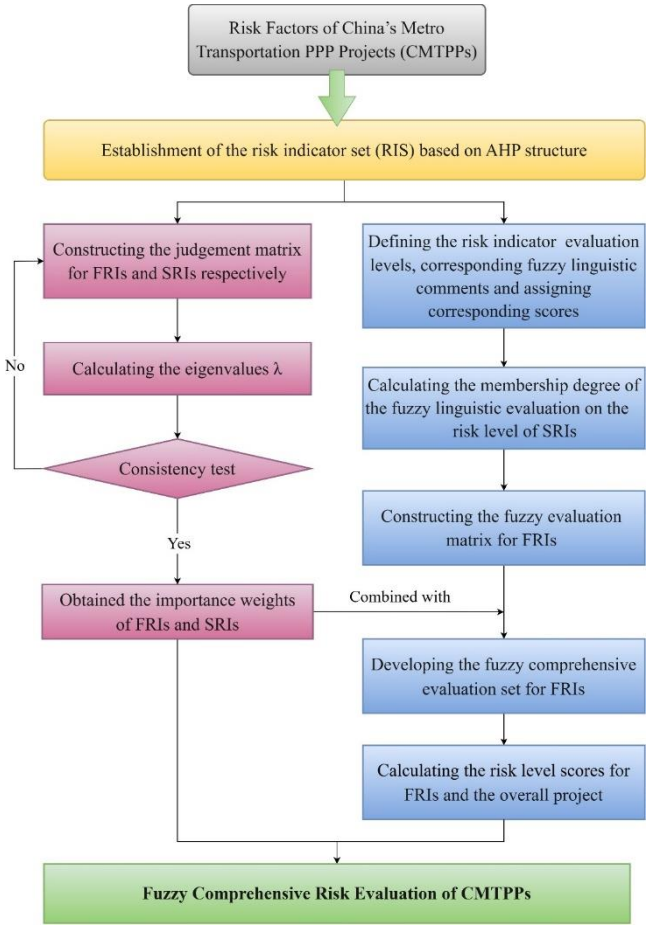

Fig. 2: The proposed fuzzy comprehensive risk evaluation model.

2.3 Establishing the risk indicator set

Based on a comprehensive literature review and in-depth analysis, this paper establishes a comprehensive risk indicator set for CMTPPs. To ensure a thorough and informative collection of risk factors, relevant literature on PPP risk factors published in journals from 2005 to 2024 (a 20-year span) was systematically reviewed. The initial selection of target literature was conducted using Google Scholar, employing key search terms such as "PPP, China, risk factors, risk management, risk assessment/evaluation, infrastructure, metro transportation, and Public-Private Partnership." To enhance the reliability of the sources, the search criteria was further refined: (1) only journal papers are

considered; (2) publications are required to originate from reputable sources, such as journals with an impact factor greater than 1, preferably published by reliable journal publishers, such as ScienceDirect, Emerald, and ASCE. Following a rigorous screening, a total of 34 journal papers from 23 different journals were ultimately selected for this study.

Subsequently, through in-depth analysis of the literature and content summarization, the authors initially identified 11 risk dimensions and 32 risk factors that are applicable to CMTPPs, and summarized them into a cross-reference table (see Appendix for details) to comprehensively present the literature sources for identifying each risk factor. On this basis, the authors further invited five (5) experts for the validation of the 32 initial risk factors. These experts all have at least 15 years of work experience, and more than 5 years of practical PPP project involvement. Subsequently, expert validation resulted in the incorporation of 13 additional risk factors, which are shown in italics in Table 1. Thereafter, the hierarchical structure of AHP was applied to construct the risk indicators set for CMTPPs, with the risk of CMTPPs as the target layer, the 11 risk dimensions as the first-level risk indicators and the 45 risk factors as the second-level risk indicators, as shown in Table 1.

Table 1: The comprehensive risk indicator set for CMTPPs.

Target Layer	First-level Risk Indicators	Second-level Risk Indicators
The Risk of CMTPPs (A)	Political Risks (B1)	Government instability (C1-1)
		Poor government credit (C1-2)
		Corruption (C1-3)
		Government intervention (C1-4)
		Government expropriation (C1-5)
		Political decision error (C1-6)
	Financing Phase Risks (B2)	*Project attraction risk (C2-1)*
		Financing feasibility risk (C2-2)
		High finance cost (C2-3)
	Legal Risks (B3)	Immature legal environment (C3-1)
		Changes in laws and regulations (C3-2)
		Environmental issues (C3-3)
	Economic Risks (B4)	Inflation (C4-1)
		Foreign exchange fluctuations (C4-2)
		Interest rate changes (C4-3)
	Social Risks (B5)	Public opposition (C5-1)
		Land acquisition (C5-2)
	Project Selection Risks (B6)	*Competition risk (exclusive right) (C6-1)*
		Project demand risk (C6-2)
	External Risks (B7)	Poor geological environment (S7-1)
		Force majeure (C7-2)
		Risk of third-party (C7-3)
	Design Phase Risks (B8)	*Unexpected design changes (C8-1)*
		Design problems (C8-2)
	Construction Phase Risks (B9)	Construction cost overruns (C9-1)
		Late approval and permit (C9-2)
		Unfair contract clauses (C9-3)
		Completion delays risk (C9-4)
		Low construction quality (C9-5)
		Delay in supply (C9-6)
		Change in the scope of work (C9-7)
		Unstable supporting utilities (CS) (C9-8)

Table 1: (continued).

Target Layer	First-level Risk Indicators	Second-level Risk Indicators
The Risk of CMTPPs (A)		Personnel risk (C9-9)
	Operational Phase Risks (B10)	Operating cost overruns (C10-1)
		Maintenance cost overruns (C10-2)
		Residual asset risk (C10-3)
		Pricing risk (C10-4)
		Unreliable government subsidy (C10-5)
		Unstable supporting utilities (OP) (C10-6)
		Low operating productivity (C10-7)
		Consortium dereliction of duty (C10-8)
		Private investor change (C10-9)
	Partnership Risks (B11)	Inadequate distribution of authorities, responsibilities, and risks (C11-1)
		Lack of commitment between partners (C11-2)
		Improper organization and coordination (C11-3)

2.4 Data Collection for the Application of FCRE Model

This research utilizes questionnaires to collect experts' opinions on the importance of risk indicators (Pairwise comparison of 9-point scales), as well as the fuzzy linguistic evaluation of the risk level of risk indicators (Low-Risk Level, Below Moderate-Risk Level, Moderate-Risk Level, Above Moderate-Risk Level, High-Risk Level) and the questionnaires are distributed and collected online. In addition, as this study attempts to apply the proposed FCRE model to an actual project case for validity testing, a China's metro transportation PPP project is then selected as a case study for model application and analysis (see Section 3 for details) to achieve the assessment of the risk level of the project. Accordingly, the questionnaire also provides participants with project information and overview of this case project for respondents' reference.

2.5 Data Analysis for the Application of FCRE Model

2.5.1 Calculating the importance weights of risk indicators

According to the FCRE model proposed in Section 2.2, after constructing the RIS, the risk indicator importance analysis should be carried out first, and the operation process is shown in Figure 2. The risk indicators belonging to each layer in the risk indicator set are evaluated in terms of their importance to that layer through a 9-point scoring system in the form of pairwise comparisons, as presented in Table 2.

After scoring the importance for each level of indicators separately by using pairwise comparisons, a judgment matrix can be constructed on this basis. In order to weaken the subjectivity of the experts' scoring, it is necessary to further test the consistency of all judgment matrices. The matrix eigenvalue value λ is applied to calculate the consistency ratio (CR), and if the value is less than 0.1, the consistency of the judgment matrix is considered satisfactory, otherwise it needs to be restructured.

Table 2: The scale of measurement in pairwise comparison by Saaty (adapted from [17,19]).

Scale	Score
Extremely importance	9
Very to extremely strongly importance	8
Very strongly importance	7
Strongly to very strongly importance	6
Strongly importance	5
Moderately to strongly importance	4
Moderately importance	3
Equally to moderately importance	2
Equally importance	1

Note. If the indicators B1 is strongly important compared to B2, it is given an importance score of 5, while B2 is scored as 1/5 compared to B1.

2.5.2 Quantitative evaluation of risk level for risk indicators

After calculating the importance weights of the risk indicators, this study adopts a fuzzy linguistic rating scale to evaluate the risk indicators by assigning different risk level scores to five risk levels, namely, "low, below moderate, moderate, above moderate, and high", as shown in Table 3 below.

Table 3: Fuzzy linguistic rating scale of the risk level of risk indicators.

Risk Levels	Risk Level Scores	Fuzzy Linguistic Comments
Level 5	1	Low-Risk Level
Level 4	2	Below Moderate-Risk Level
Level 3	3	Moderate-Risk Level
Level 2	4	Above Moderate-Risk Level
Level 1	5	High-Risk Level

Note. The scores should follow the rules of rounding to the nearest whole number. For example, if the calculated risk level is scored as 3.55, which is higher than 3.5 but lower than 4, it is considered to be 4, which is at a "Above Moderate-Risk Level.

On this basis, according to the analysis process described in the FCRE model as shown in Figure 2, the fuzzy evaluation matrix is constructed after calculating the membership degree of the fuzzy linguistic evaluation of the risk level of the SRIs. Then, the fuzzy evaluation sets and risk level scores could be obtained by combining with the weights of the SRIs, to realize the fuzzy comprehensive quantitative evaluation of both FRIs and the overall project.

1) Determining the fuzzy evaluation scale

The fuzzy evaluation rating of the risk level of SRIs in this study is divided into five levels as below, as referring back to Table 3.

$$V = (V_1, V_2, \cdots, V_n) = (Low, Below\ moderate, Moderate, Above\ moderate, High) \quad (1)$$

2) Calculating the membership degree and constructing fuzzy membership matrix

Each risk indicator from the second-level risk indicators set $S_k = \{S_{k1},\ S_{k2},\ \ldots\ S_{kn}\}$ is evaluated individually as first, R is the fuzzy membership matrix.

$$R_k = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{21} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{q1} & r_{q2} & \cdots & r_{qn} \end{bmatrix} \quad (2)$$

$$r_{ij} = \frac{V_{ij}}{\sum_{j=1}^{n} V_{ij}}, (i = 1, 2, \ldots, \mathrm{q};\ j = 1, 2, \ldots, \mathrm{n}) \quad (3)$$

where r_{ij} is obtained by collating the results of the expert's evaluation of the risk level of the risk indicator S_{ij}. For instance, r_{11} represents the proportion of experts who prefers the comment V_1 when evaluating the second-level risk indicator.

3) Developing the fuzzy comprehensive evaluation set for FRIs

In this step, combining the weight vector A_i of the SRIs with the fuzzy evaluation matrix R_i by applying $P_i = A_i * R_i$, and the fuzzy comprehensive evaluation set of the FRIs is obtained:

$$P = AR = \left(a_{i1}, a_{i2},\ \ldots\ a_{ip}\right) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{21} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{q1} & r_{q2} & \cdots & r_{qn} \end{bmatrix} = \left(p_1, p_{2,\cdots} p_n\right) \quad (4)$$

4) Calculation of risk level scores

Referring to the risk level scores set in the Table 3, the risk level scores for the 11 FRIs and the overall project could be calculated as following:

$$D_1 = \left(p_1, p_{2,}\ p_{3,}\ p_{4,}\ p_5\right) * \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} \quad (5)$$

$$D_P = (a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, a_{11})^* \begin{bmatrix} d1 \\ d2 \\ d3 \\ d4 \\ d5 \\ d6 \\ d7 \\ d8 \\ d9 \\ d10 \\ d11 \end{bmatrix} \quad (6)$$

2.6 Formation of Risk Management Strategies for Key Risk Indicators

Afterwards, this study selects key FRIs with risk levels of above-moderate and higher as the research focus to expand the research on risk management countermeasures for general CMTPPs. Combined with the expert interpretation of the quantitative results, this study proposes targeted and practical risk management strategies for CMTPPs based on the relevant risk management literature and expert interviews, from the three main stages of risk event management, namely, ex-ante prevention, mid-control and ex-post response by considering the different perspectives of government and private sector. This process ensures the comprehensiveness and consistency of the risk management process, and enhances the effectiveness and practicality of the management strategies with graphical visualization of the output (refer to Figure 3-7 for details).

The selection criteria for the expert in this section is mainly based on the experts' familiarity with and experience in PPP projects and relevant risk management, as evidenced by having more than 15 years of working experience, of which more than 5 years are directly related to PPP projects, and have participated in at least 1 or more PPP projects. As described in Subsection 2.4, this paper applies the actual project case to validate the proposed FCRE model, therefore, in the invitation of experts, after communication and consultation with the PPP project company, combined with the actual situation and willingness to participate of the project related management personnel, a total of four experts who meet the selection criteria are invited to participate in the study.

The experts' interpretation of the research results is used as an important input and reference for the risk management strategies for key risk indicators proposed in this paper, on the basis of which insights on risk management countermeasures are provided for CMTPPs from a comprehensive perspective.

Simultaneously, in order to gain a better understanding of the experts' views and perceptions of the key risk indicators, as well as their interpretation and constructive recommendations of the corresponding risk management strategies, this paper designs the following questions based on the results of the data analysis of the project cases in order to obtain more in-depth and meaningful insights in the experts' interpretation session:

1) Do you agree with the data analysis results (including importance weights and ranking, risk level scores and ranking, etc.) of the case application in this study? If not, which parts do you have objections to? Please kindly point them out.

2) If you endorse the results of the fuzzy comprehensive risk evaluation of the case project, please kindly analyze the key risk indicators in the risk evaluation results and offer your insights on the corresponding ranking, considering the actual implementation of the project as well as the content of the work you have been involved in the project and your knowledge of the project's risk management. Meanwhile, please note that it is preferable to provide a comprehensive discussion combining the current status of the application of the PPP model in China, and to provide a separate analysis of each key risk indicator.

3) Please propose risk management strategies for each key risk indicator from the different perspectives of the government and the private sector, as well as from the perspective of the three main phases of risk event management, i.e., ex-ante prevention, mid-control and ex-post response. And please try to put forward effective and practical risk management suggestions in the light of the actual situation of the project, project risk management mechanisms and norms, or drawing on the experience of other similar historical projects.

3 Case Application

3.1 Case Project Introduction

As the first whole-line metro project in Tianjin to be implemented in PPP model, Tianjin Metro Line 7 Phase I (TML7P1) project is expected to substantially alleviate traffic congestion in Tianjin's urban core when completed. The estimated total investment of TML7P1 project is RMB 26.897 billion, of which the PPP project company invests about RMB 19.681 billion yuan, and the remaining part is invested by the government who is also responsible for land acquisition, demolition and relocation and other preliminary work. TML7P1 project has a total length of 26.53 km, with 21 stations, all of which are underground, and passes through 6 administrative districts, making it one of the most central lines in Tianjin. TML7P1 was commenced in July 2019, with a concession period of 26 years, where the planned construction period is 4.5 years and the operation period is 21.5 years, and is expected to open for operation within the end of 2024.

The PPP project company, China Construction (Tianjin) Railway Investment and Development Co., Ltd. was established by Tianjin Rail Transit Group Limited Company as the representative of the government sector's capital contribution to the project, and CSCEC as the leader of the private capital consortium. The percentage of project capitalization is 40%, and the remaining project loan portion will be financed by project company through bank financing. The equity ratio of the representative of the government is 49%, and the equity ratio of the private capitals is 51%.

The Tianjin Municipal People's Government has authorized the Tianjin Municipal Housing and Urban-Rural Development Commission and the Tianjin Municipal Transportation Commission as the implementation authorities of the project to sign the "Government and Private Capital Cooperation Agreement" with the private capital consortium, and the implementation authorities will enter into the "PPP Project Contract" with the PPP project company after the project company has been established. The content of the Contract is mainly to authorize the PPP project company to be responsible for the investment and financing and the construction of the TML7P1, as well as operation, maintenance, upgrading and reconstruction, preparation and organization of the implementation of the additional investment plan during the cooperation period, and to obtain the corresponding ticketing revenue, non-ticketing business revenue and the feasibility gap subsidy provided by the government side to cover the reasonable return on investment and operation of the TML7P1 project.

3.2 Results of the Fuzzy Comprehensive Risk Evaluation for TML7P1 Project

A total of 69 experts from the field of China's metro transportation PPP projects participated in the questionnaire survey as respondents, and the response rate of the questionnaire is 100%. Among them, approximately one-third of them are from PPP project companies and two-thirds of them are from PPP project contractors. Subsequently, after analyzing and processing the collected data according to the procedure described in Section 2.5, Table 4 summarizes the importance weights of the first and second level risk indicators and the consistency ratios of the judgment matrices.

Table 4: The importance weights of first-level and second-level risk indicators in descending order.

Target Layer	First-level Risk Indicators & Weights	Consistency Ratio (CR)	Second-level Risk Indicators	Weights	Overall weights
A CR=0.0896	B1 0.1668	0.0048	C1-4	0.2919	0.0487
			C1-6	0.2298	0.0383
			C1-3	0.1889	0.0315
			C1-2	0.1520	0.0253
			C1-1	0.0951	0.0159
			C1-5	0.0424	0.0071
	B2 0.1496	0	C2-2	0.4518	0.0747
			C2-3	0.3536	0.0500
			C2-1	0.1946	0.0249
	B4 0.1400	0.0016	C4-3	0.5671	0.0794
			C4-1	0.2717	0.0380
			C4-2	0.1612	0.0226
	B9 0.1361	0.0676	C9-1	0.2320	0.0316
			C9-4	0.1523	0.0207
			C9-2	0.1463	0.0199

			C9-7	0.1221	0.0166
			C9-3	0.1020	0.0139
			C9-5	0.0947	0.0129
			C9-6	0.0892	0.0121
			C9-8	0.0413	0.0056
			C9-9	0.0202	0.0027
	B11 0.0885	0.0083	C11-1	0.3547	0.0314
			C11-3	0.3539	0.0313
			C11-2	0.2914	0.0258
	B10 0.0883	0.0007	C10-1	0.1903	0.0168
			C10-4	0.1758	0.0155
			C10-5	0.1609	0.0142
			C10-2	0.1381	0.0122
			C10-6	0.1176	0.0104
			C10-7	0.0995	0.0088
			C10-8	0.0581	0.0051
			C10-3	0.0402	0.0035
			C10-9	0.0195	0.0017
	B3 0.0712	0.0385	C3-1	0.4845	0.0345
			C3-2	0.3356	0.0239
			C3-3	0.1798	0.0128
	B6 0.0562	0	C6-2	0.6255	0.0351
			C6-1	0.3745	0.0210
	B5 0.0367	0	C5-2	0.7500	0.0275
			C5-1	0.2500	0.0092
	B8 0.0345	0	C8-1	0.7042	0.0243
			C8-2	0.2958	0.0102
	B7 0.0321	0.0061	C7-3	0.4573	0.0147
			C7-1	0.3717	0.0119
			C7-2	0.1710	0.0055

Table 5 presents the degree of membership of the experts' fuzzy linguistic evaluations of the risk level for each second-level risk indicator.

Table 5: The degree of membership of the fuzzy linguistic evaluation on the risk level of second-level risk indicators.

Second-level Risk Indicators	Low-Risk Level	Below Moderate-Risk Level	Moderate- Risk Level	Above Moderate-Risk Level	High-Risk Level
C1-1	0.05	0.05	0.15	0.22	0.53
C1-2	0.04	0.04	0.10	0.20	0.62
C1-3	0.07	0.04	0.08	0.30	0.51
C1-4	0.02	0.06	0.07	0.18	0.67
C1-5	0.09	0.11	0.08	0.09	0.63
C1-6	0.05	0.07	0.09	0.15	0.64
C2-1	0.05	0.08	0.12	0.35	0.40
C2-2	0.04	0.05	0.11	0.30	0.50
C2-3	0.07	0.05	0.06	0.38	0.44
C3-1	0.04	0.11	0.09	0.15	0.61
C3-2	0.11	0.15	0.17	0.22	0.35
C3-3	0.07	0.09	0.07	0.22	0.57
C4-1	0.06	0.12	0.16	0.25	0.41
C4-2	0.04	0.07	0.11	0.33	0.44
C4-3	0.06	0.07	0.09	0.31	0.48
C5-1	0.37	0.28	0.20	0.09	0.06
C5-2	0.32	0.26	0.17	0.15	0.10
C6-1	0.07	0.30	0.15	0.26	0.22
C6-2	0.15	0.17	0.33	0.17	0.17
C7-1	0.32	0.24	0.22	0.14	0.08
C7-2	0.30	0.32	0.20	0.12	0.07

C7-3	0.28	0.32	0.20	0.14	0.06
C8-1	0.22	0.48	0.13	0.11	0.07
C8-2	0.20	0.28	0.24	0.17	0.11
C9-1	0.06	0.03	0.16	0.22	0.54
C9-2	0.05	0.05	0.15	0.22	0.53
C9-3	0.04	0.04	0.10	0.20	0.62
C9-4	0.07	0.04	0.08	0.30	0.51
C9-5	0.02	0.06	0.07	0.18	0.67
C9-6	0.09	0.11	0.08	0.09	0.63
C9-7	0.05	0.07	0.14	0.21	0.54
C9-8	0.04	0.07	0.11	0.21	0.57
C9-9	0.03	0.09	0.09	0.24	0.55
C10-1	0.06	0.06	0.12	0.30	0.46
C10-2	0.10	0.20	0.15	0.15	0.40
C10-3	0.15	0.25	0.15	0.20	0.25
C10-4	0.08	0.09	0.16	0.24	0.43
C10-5	0.10	0.15	0.15	0.20	0.40
C10-6	0.12	0.15	0.15	0.20	0.38
C10-7	0.17	0.15	0.13	0.20	0.35
C10-8	0.14	0.16	0.18	0.22	0.30
C10-9	0.22	0.25	0.15	0.20	0.18
C11-1	0.12	0.14	0.17	0.24	0.33
C11-2	0.12	0.23	0.28	0.25	0.12
C11-3	0.13	0.12	0.25	0.24	0.26

The risk level scores for each of the 11 FRIs and the overall risk level score for the TML7P1 project are calculated separately. The calculation of the first FRI and the overall project risk level is illustrated below as an example. For the remaining 10 FRIs, the calculation process is the same and the results are summarized in Table 6.

1) Political Risks

The fuzzy membership matrix for Political risks is:

$$R_1 = \begin{bmatrix} 0.05 & 0.05 & 0.15 & 0.22 & 0.53 \\ 0.04 & 0.04 & 0.10 & 0.20 & 0.62 \\ 0.07 & 0.04 & 0.08 & 0.30 & 0.51 \\ 0.02 & 0.06 & 0.07 & 0.18 & 0.67 \\ 0.09 & 0.11 & 0.08 & 0.09 & 0.63 \\ 0.05 & 0.07 & 0.09 & 0.15 & 0.64 \end{bmatrix} \tag{7}$$

According to the formula: $P_1 = A_1 D_1$

$$P_1 = (0.0951, 0.1520, 0.1889, 0.2919, 0.0424, 0.2298) * \begin{bmatrix} 0.05 & 0.05 & 0.15 & 0.22 & 0.53 \\ 0.04 & 0.04 & 0.10 & 0.20 & 0.62 \\ 0.07 & 0.04 & 0.08 & 0.30 & 0.51 \\ 0.02 & 0.06 & 0.07 & 0.18 & 0.67 \\ 0.09 & 0.11 & 0.08 & 0.09 & 0.63 \\ 0.05 & 0.07 & 0.09 & 0.15 & 0.64 \end{bmatrix} \tag{8}$$

$$= (0.0452, 0.0567, 0.0891, 0.1988, 0.6103)$$

The risk level score of Political risks indicator is:

$$D_1 = (0.0452, 0.0567, 0.0891, 0.1988, 0.6103) * \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{bmatrix} = 4.27 \tag{9}$$

2) The overall risk level score of TML7P1 project

Combined with the weights of the FRIs calculated in the previous section, the overall risk level score of TML7P1 project is obtained as shown below:

$$D_P = (0.1668,0.1496,0.0712,0.1400,0.0367,0.0562,0.0321,0.0345,0.1361,0.0883,0.0885)* \begin{bmatrix} 4.2726 \\ 4.0956 \\ 3.9700 \\ 4.0227 \\ 2.3850 \\ 3.1035 \\ 2.3928 \\ 2.4624 \\ 4.2101 \\ 3.4884 \\ 3.3250 \end{bmatrix} = 3.77 \quad (10)$$

Table 6: Summary of the risk level scores of FRIs for TML7P1 project.

Ranking	First-level Risk Indicators	Risk Level Scores	Risk Evaluation Level
1	Political Risks	4.27	Above Moderate-Risk Level
2	Construction Phase Risks	4.21	Above Moderate-Risk Level
3	Financing Phase Risks	4.10	Above Moderate-Risk Level
4	Economic Risks	4.02	Above Moderate-Risk Level
5	Legal Risks	3.97	Above Moderate-Risk Level
6	Operation Phase Risks	3.49	Moderate-Risk Level
7	Partnership Risks	3.33	Moderate-Risk Level
8	Project Selection Risks	3.10	Moderate-Risk Level
9	Design Risks	2.46	Below Moderate-Risk Level
10	External Risks	2.39	Below Moderate-Risk Level
11	Social Risks	2.39	Below Moderate-Risk Level
	Overall project (TML7P1)	3.77	Above Moderate-Risk Level

With the overall risk level of the TML7P1 project is 3.77, which is rounded to 4, this indicates that the overall risk level is above moderate. According to the calculation results of the 11 FRIs (see Table 6), it can be identified that the risk level of the first 5 FRIs, led by “Political Risks”, is above moderate, occupying more than 45% of the total indicators. In the course of project implementation, these indicators should be highly considered and monitored, and a detailed risk management strategy should be formulated. Nevertheless, the remaining six risk indicators are all classified as moderate risk level or below, which represents that they could be reasonably regulated during project implementation by maintaining a moderate level of attention and supervision, along with timely risk control and feedback. The discussion of the first five FRIs from the experts’ interviews is presented next.

3.3 Expert Interpretations of Research Findings

In this section, four experts with knowledge of the TML7P1 project situation and practical experience in CMTPPs’ risk management are invited for an in-depth discussion. This session is conducive to exploring the views of PPP participants (the government and private sector) from different perspectives on risk management strategies, as well as fully interpreting and expanding the findings of the study. Table 7 summarizes the profile of the 4 experts.

Table 7: The profile of the 4 experts invited for results interpretation.

Expert No.	Occupation	Work Experience (years)	Work Experience in PPP (years)	Number of PPP projects participated in
1	Project Manager	20	10	2
2	Chief Project Engineer	18	9	1
3	Department Manager	22	12	2
4	Project Manager	21	11	2

Experts point out that as the first entire line in Tianjin to adopt the PPP model, the performance of TML7P1 project has received much attention. In addition, the concession period of PPP projects is relatively long, and in recent years, China’s PPP model is in the period of standardization, the project will inevitably be affected by policy changes, that is, it will involve the modification or supplementation of the contract between the participants, and also subsequently have a number of impacts on the project's construction, operation, and risk-sharing, etc. [20, 21]. Furthermore, the TML7P1 project is characterized by a large number of continuous interchange stations, a large number of passengers, and high construction difficulties, etc., thus the research on its risk evaluation and management is of great

practical significance. Combining the results of the above fuzzy comprehensive risk evaluation, the experts interpret the risk level of the project as follows.

1) Political Risks

As the top-ranked FRI of risk level, its impacts are far-reaching and wide-ranging. Due to the large investment amount and long concession period of PPP projects, it is highly vulnerable to policy changes [22]. For example, due to the influence of the Covid-19 Pandemic, the National Government of China has tightened overall spending on PPP projects, resulting in a downward trend in the landing rate of PPP projects [23]. Accordingly, some of the preliminary work undertaken by the government, such as traffic guidance, land acquisition, demolition and relocation, may lead to an increase in the construction period and a corresponding delay in the completion time. Once occurred, this not only results in an increase in interest during the construction period but also leads to a delay in operations, which may shorten the time to obtain a return on investment, resulting in operational revenues not meeting expectations [24].

2) Construction Phase Risks

The route of TML7P1 project passes through six administrative districts, it is a north-south skeleton line through the city center. Due to the geographical location of most stations are in busy areas, the road diversions and disconnections, construction site restrictions, night construction noise and etc. have become the major difficulties. Moreover, TML7P1 project has numerous interchange stations, some interchange stations even reach the fourth floor underground, which adds a lot of difficulties to the construction. Many of the construction difficulties also set records in Tianjin, such as the deepest underground diaphragm wall in the history of Tianjin's rail transit construction, which was 70.287 meters in depth. In addition, TML7P1 project is expected to have a high flow of passengers in the future, thus the train type is planned to use 6A configuration. The length of the train and station platforms are longer compared to other lines. The width of the track is also wider, which brings considerably more difficulties for the construction of the line interchanges, and the risks faced are consequently higher.

3) Financing Phase Risks

TML7P1 project as the first entire metro line applying the PPP model, marks an innovative breakthrough in the investment and financing mode of Tianjin's urban rail transit construction. Experts indicate that the private capital has been actively introduced and PPP model has been actively carried out in the stock of construction projects and new projects, which not only accelerated the pace of construction, but also alleviated the pressure on the financial burden of the Tianjin government. However, as the project suffered from the Covid-19 pandemic after the commencement of construction, it faced a series of impacts caused by the project funding constraints caused by the pandemic, the tightening of the Tianjin municipal government's investment in infrastructure and its financial liabilities [25], and there was a situation in which the project funding could not be made available in a timely manner, which might lead to delays in the schedule caused by the pause of the construction work. Thus, it can also be seen that such force majeure factors pose a greater threat to project finance, which demonstrates the importance of having a robust and resilient financing environment [26].

4) Economic Risks

The design estimate of TML7P1 project was prepared in March 2016, but the actual construction started in 2019. Over time, through inflation, the labor cost and material cost are rising, especially after experienced the Covid-19 Pandemic, the price of steel materials such as steel reinforcing bar raised after May 2021, which leads to the increase in the construction cost consequentially [27]. However, due to the lack of sound and specific price change subsidy clauses in the PPP contract, the construction contract is vague on the adjustment of the contract price due to the price increase of materials, and contractors are easily exposed to the risk of cost overruns.

5) Legal Risks

The fuzzy comprehensive risk evaluation model proposed and applied in this study is relatively consistent with the actual situation of the TML7P1 project from the point of view of the current progress of project implementation and the performance of the risk level. The overall risk level of the project is above moderate, which to a certain extent indicates that the effectiveness of the implementation of risk management and control of the project still needs to be improved. Experts point out that China's PPP legislation has not yet been formally introduced, and the lack of legislative guarantees is closely related to the healthy application of the PPP model and its effective implementation of risk management [28], while unified legal norms also have an all-encompassing impact on the efficiency and productivity of project execution. Therefore, the early enactment of PPP legislation in China may greatly improve the PPP industry environment and enhance the functionality of PPP risk management simultaneously.

4 Discussions and Proposed Risk Management Strategies for Key Risk Indicators

Based on the interviews with experts, the whole lifecycle of PPP project is discussed from the three phases of ex-ante prevention, mid-control and ex-post response to risk events. Five key FRIs (Political Risks, Construction Phase Risks, Financing Phase Risks, Economic Risks and Legal Risks) which are above moderate-risk level are discussed coherently. Combining their rich experience in the industry and the current situation and development trend of CMTPPs, the experts conduct a comprehensive consideration and integrated analysis of key risk indicators, and put forward suggestions on the strategic management of CMTPPs' risks from a holistic perspective. Subsequently, this study refers to the experts' opinions to propose targeted management countermeasures for each key risk indicator, which are presented and elaborated through diagrams and explanations as shown in Figure 3-7. The valuable inputs of the four experts provided for the usefulness and effectiveness of the content of the risk management strategies.

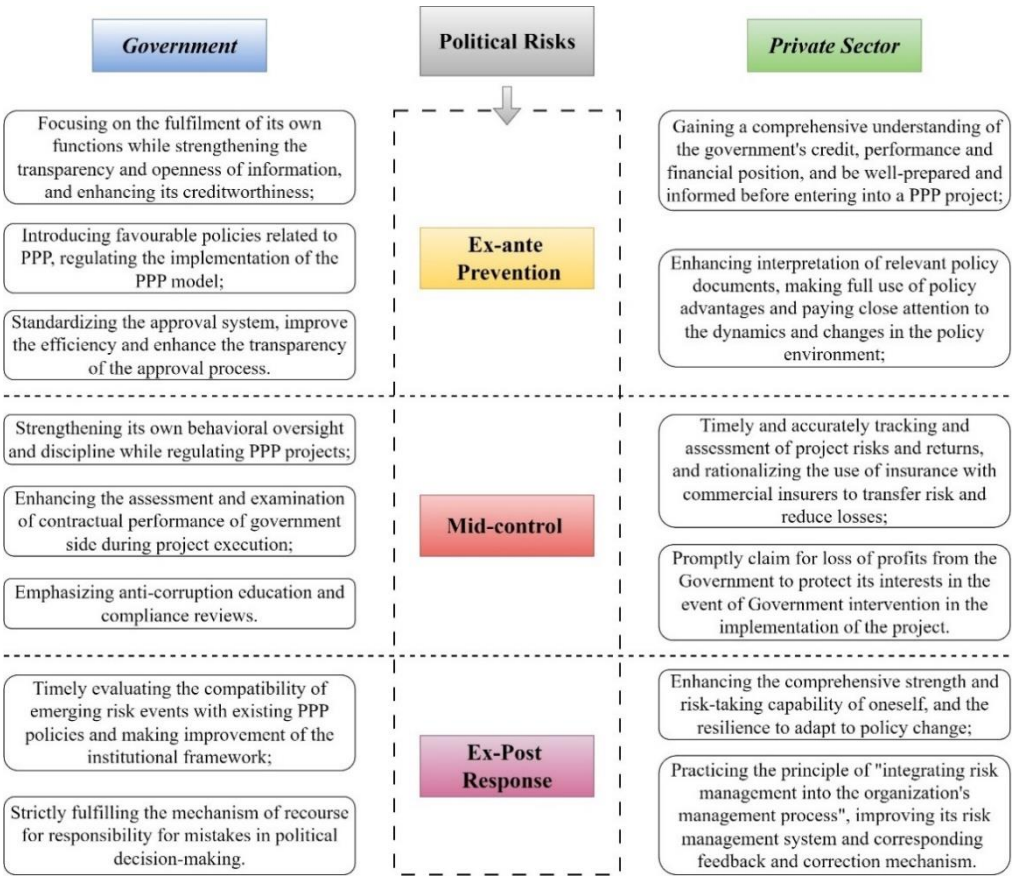

Fig. 3: The proposed risk management strategies for Political Risks.

First of all, the experts indicate that given the far-reaching impact of changes in the macroeconomic situation and policies, which may bring consequences such as financing difficulties and project delays, it is a great pressure and challenge for private capitals. Therefore, private sector should strengthen the understanding of relevant policy documents, make full use of the policy advantages, and pay close attention to the economic environment [29]. While in order to promote the smooth implementation of PPP projects, the government may introduce a series of favorable policies to promote the implementation of the project (refer to Figure 3 for details), such as the relevant tax and other preferential policies. More specifically, the Government Work Report has pointed out that efforts will be made to broaden the financing channels of PPP, and that for qualified PPP projects, the loan period can be up to 30 years, and the loan interest rate can be appropriately preferential; moreover, the "PPP Regulations (Draft for Public Comments)" also highlights that 'the financial expenditures agreed upon in the agreement of the cooperation project should be fully incorporated into the annual budget, and funds should be distributed promptly after approval in accordance with the prescribed procedures.

More importantly, the performance of the cooperation project agreement shall not be affected by the adjustment of administrative divisions, change of government, adjustment of the institutions or functions of the relevant government departments, or the change of persons in charge. It is evident that the optimization of PPP-related policies provides a strong backing for project implementation and fundamentally reduces the negative impact of policy-driving factors on the management of the entire PPP project [30].

For the risk factors in the construction phase, for some potential problems of the project such as price adjustments, design changes, etc., it should be stipulated as explicitly as possible in the contract to provide a more reasonable scheme to protect the interests of both parties (refer to Figure 4 for details). Moreover, emphasizing the allocation of responsibility of the parties to the provisions of the contract to improve the integrity of the contract and reduce uncertainty [31]. Thereby avoiding disputes between the two parties due to possible opportunistic behaviour of one party to the contract, which could result in extension, disputes or even suspension of work. If there is a delay in the schedule, the private capital should have a flexible dynamic adjustment mechanism to be implemented in a timely manner [32], such as adopting reasonable countermeasures to enhance work efficiency and optimize work schedule and resource allocation as indicated in Figure 4 below.

Combined with the actual situation of TML7P1 project, construction changes have begun to appear, experts recommend that private sector should fully understand the planning and design requirements, and coordinate and adjust with the design unit in time when special circumstances arise in the construction process, to minimize the impact on the subsequent stages of construction. At the same time for the changes that have occurred in the content or scope of the work, private sector should enhance their work productivity, provide adequate material resources for construction to ensure a timely and effective response to changes in construction work, as emphasized in Figure 4.

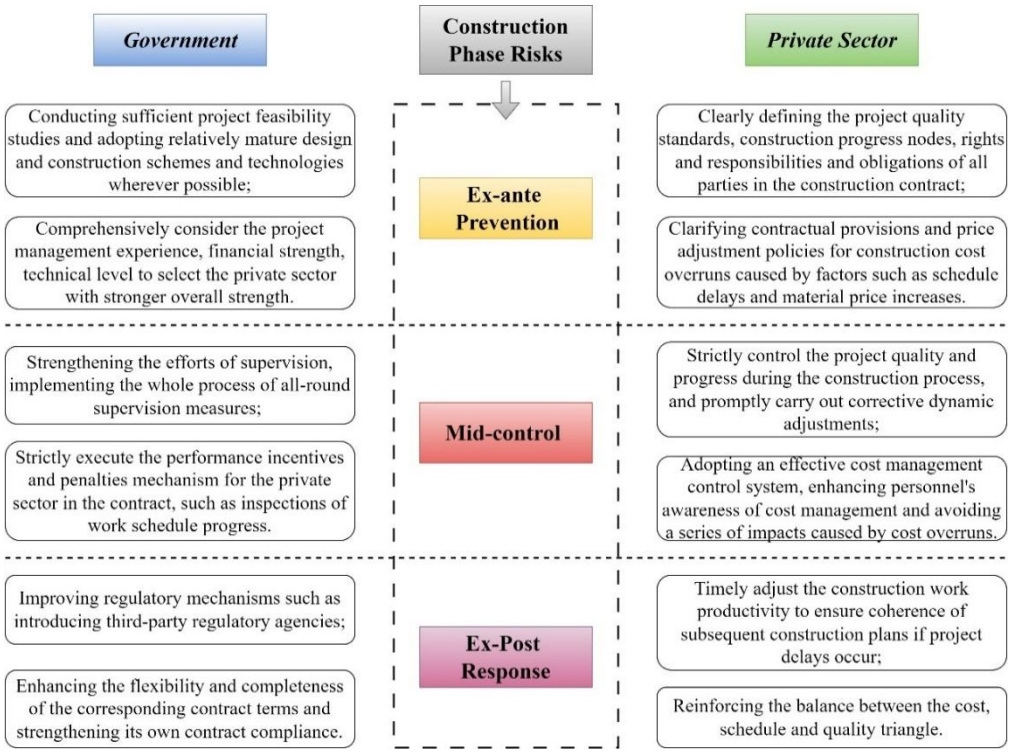

Fig. 4: The proposed risk management strategies for Construction Phase Risks.

It should also be noted that the private sector should strengthen corporate publicity and image maintenance, and comprehensively improve corporate credit rating to obtain a more favourable public image for financing [33]. Moreover, private sectors should accurately assess the risk and difficulty of financing considering their own strengths, and maximize the continuity and reliability of financing by cooperating with financial institutions with higher credit ratings (refer to Figure 5 for details). Simultaneously, the governments should also enhance the transparency and openness of information, supervision, and contract performance credit [5]. More importantly, governments should not ignore the

strength gap and disparity between SOEs and POEs, and should endeavour to provide more policy support and financing support for POEs while innovating and broadening the financing platform as highlighted in Figure 5, thereby playing a positive role in guiding the development of PPP model in China.

Particularly, for SOEs and POEs, the elimination of policy support and financial discrimination is a priority. At present, the financing difficulties of SOEs are not the same as those of POEs. Then, in view of the different economic development status of developed and developing regions, financial institutions should increase their support for less developed regions in China. Moreover, policy stability and continuity are the focus, promoting the deep integration of macro and micro policies, as policy instability is a major concern for financial institutions and may affect their willingness to cooperate.

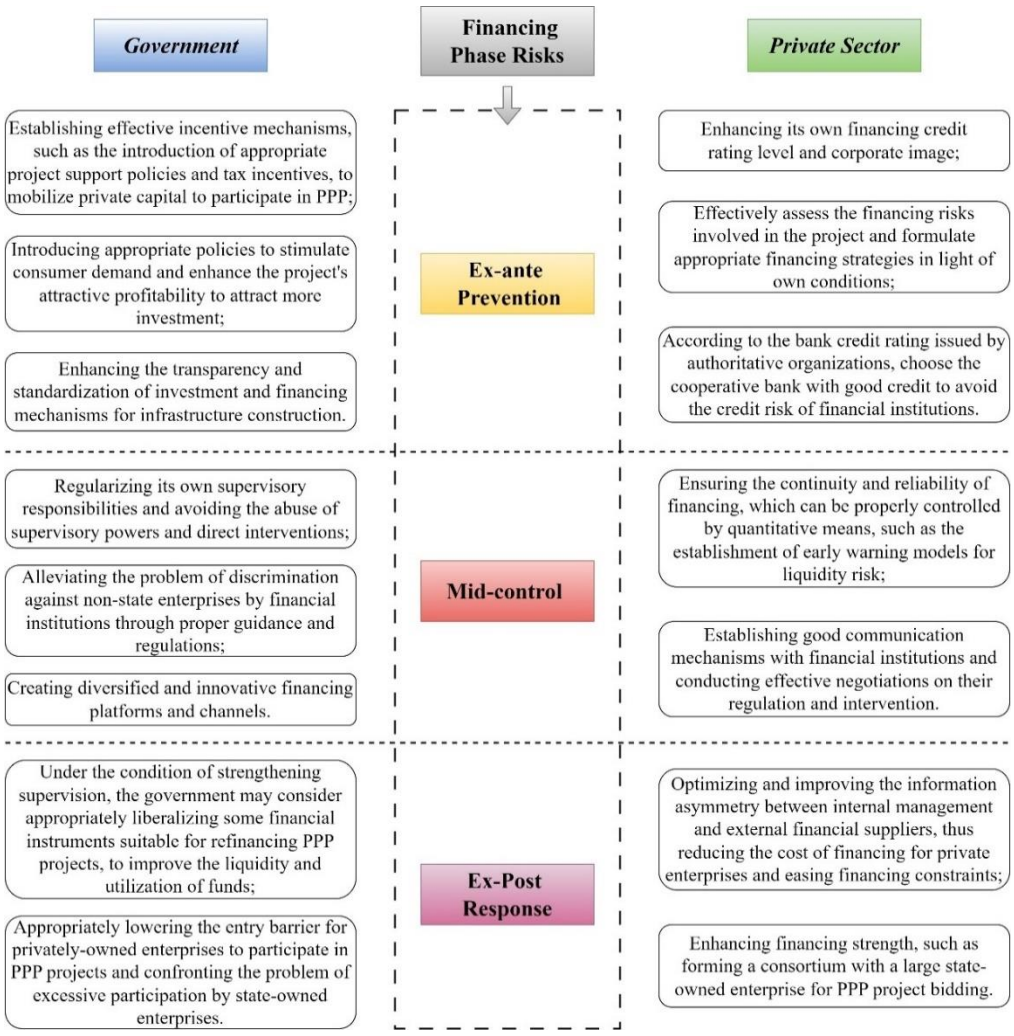

Fig. 5: The proposed risk management strategies for Financing Phase Risks.

Economic risks can to some extent be considered inseparable from financing risks. The impact of the uncertainty of changes in market interest rates on the financing of PPP projects should not be underestimated [34]. Generally speaking, interest rates mainly have an impact on loans during the construction period of PPP projects, which in turn may affect project costs and profits. This means that the government's monetary policy is of paramount importance and should play its role as a regulator of the economic market while participating in the project implementation process, as illustrated in Figure 5. Simultaneously, the private sector needs to be aware of the changes in the financial markets, and must have a clear positioning and judgement of its own financial capacity, such as loan repayment ability. In addition, it should also focus on improving project profitability and productivity, fully utilizing reasonable financial instruments to reduce the impact of interest rate changes and other economic risk factors brought about (refer to Figure 6 for details).

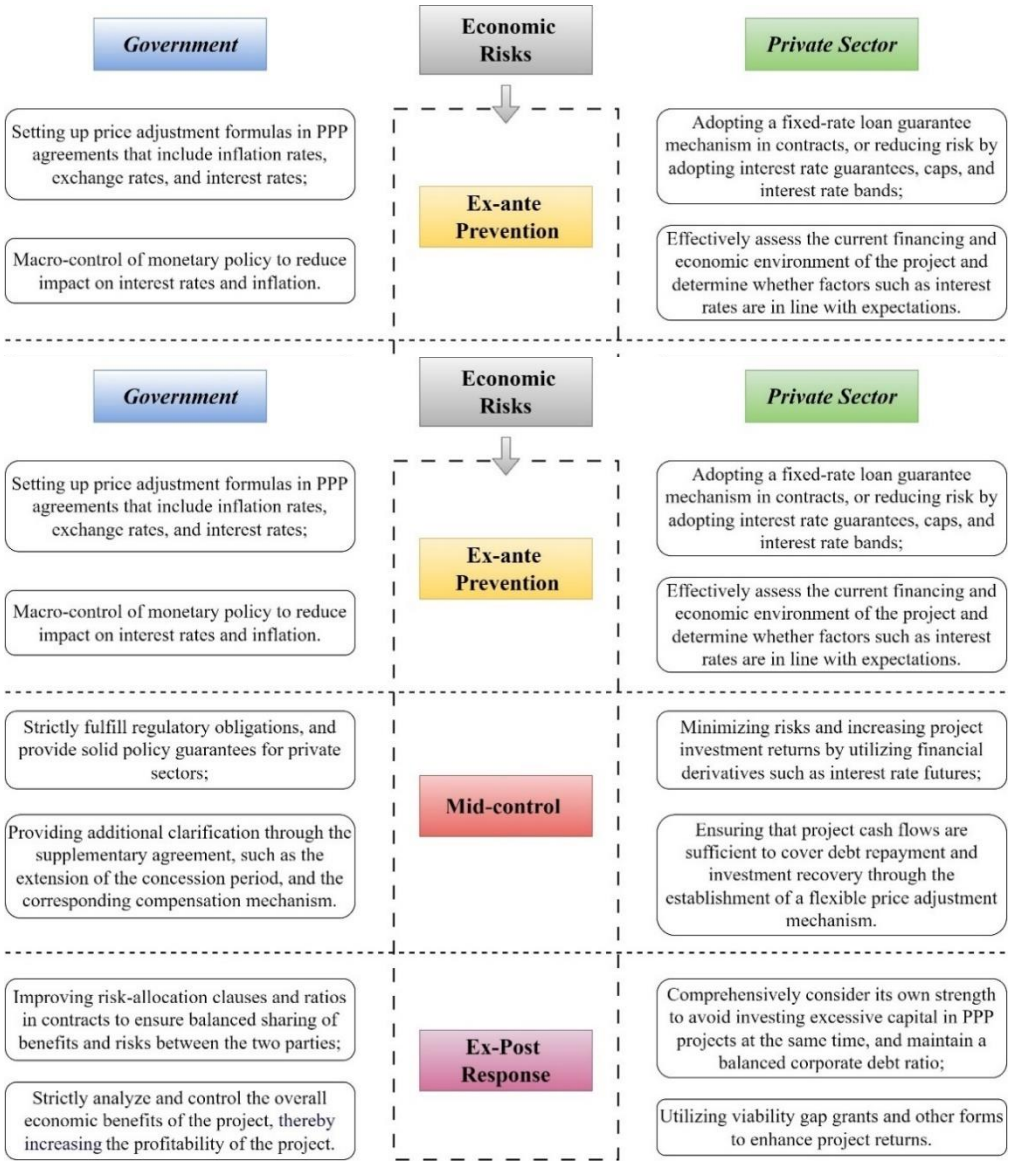

Fig. 6: The proposed risk management strategies for Economic Risks.

Non-negligibly, based on the current situation of China's PPP industry, sound legal environment is a must to improve the risk management of PPP projects [35,36]. The introduction of sound PPP legislation and policies has self-evident benefits including, but not limited to, the innovation of the financing environment of the PPP model and the enhancement of contractual performance [37], and can even be considered fundamental to the stable development of the PPP model in China. Therefore, governments should introduce PPP model-specific legal provisions and policies as early as possible to further clarify the division of rights and responsibilities of PPP project participants, so as to provide the private sector with substantive protection of interests and a basis for risk transfer, as highlighted in Figure 7. It also provides a reliable reference for the diversification of financing channels for PPP projects, as well as the contractual terms of the price adjustment mechanism involved in the economic risks, such as inflation, faced in the course of project implementation.

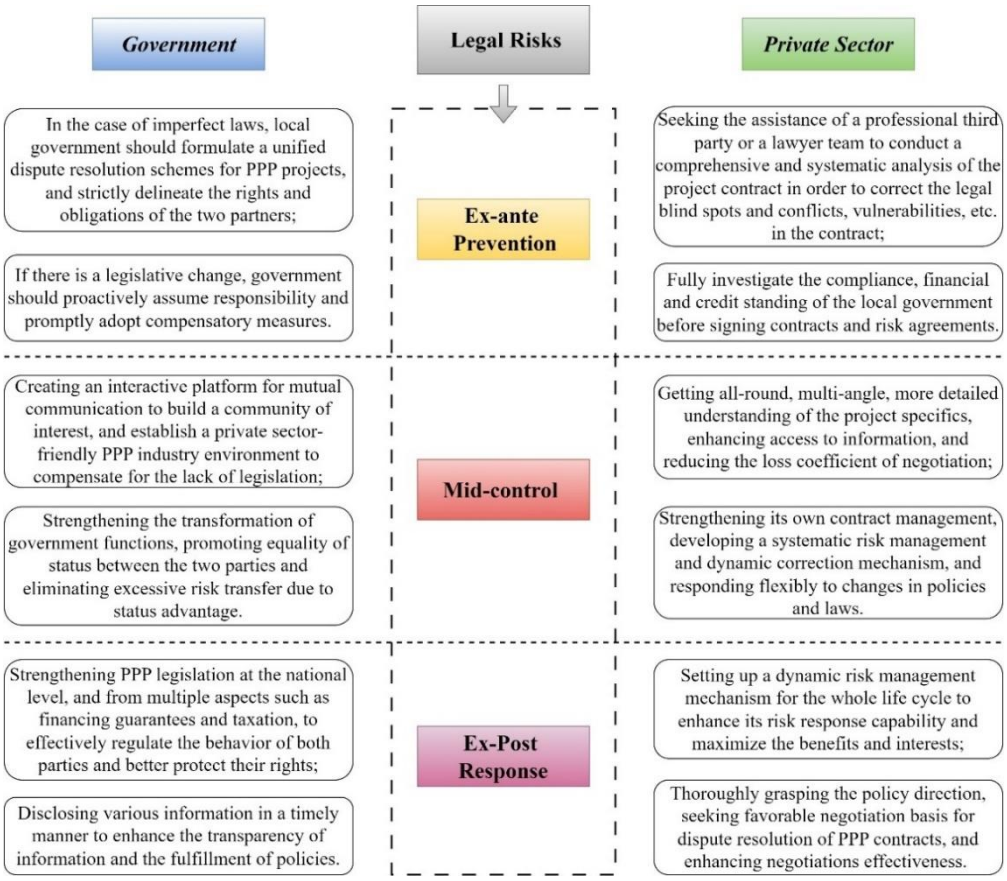

Fig. 7: The proposed risk management strategies for Legal Risks.

5 Conclusion

This study aims to provide a comprehensive and effective quantitative evaluation of the risk level of CMTPPs. The FCRE model is developed using a combination of AHP and FEC methods, and a collection of applicable risk indicators for CMTPPs is constructed through literature review and analysis for risk evaluation in subsequent research process. Subsequently, the fuzzy linguistic comments on the risk level of risk indicators based on expert opinion are collected through a questionnaire survey. The research findings show that the top five indicators with above moderate risk level are “Political, Construction, Financing, Economic and Legal Risks”. To a certain extent, the results fully reflect the significant guiding role and rooted influence of the policy and financing environments on the applications of PPP model in China. While the government plays a crucial role in introducing and regulating policies for PPP projects and in moderating the economic environment. Notably, experts emphasized the risks associated with the construction phase, which in combination with economic risks such as interest rate fluctuations and inflation, further impact the level of project risk more significantly. In addition, as the TML7P1 project experienced the Covid-19 pandemic at the beginning of the construction period, it had a non-negligible impact on the construction cost control of the project, such as the increase in the price of materials and untimely supply.

Furthermore, the lack of a well-established legal framework for PPP projects in China presents a more pervasive challenge, as a sound and sustainable legal environment is essential for project financing, risk allocation, and contract management. This issue is particularly critical in the current PPP landscape, where SOEs and POEs face imbalanced access to project resources and disproportionate financing difficulties. Thus, to enhance the standardization and sustainability of PPP project implementation in China, further regulatory improvements are necessary.

Moreover, the TML7P1 project represents the first large-scale application of the PPP model in urban rail transportation in Tianjin, with an overall risk level exceeding the moderate threshold. This highlights the stringent requirements for effective risk management and its performance monitoring. Future research could focus on evaluating the effectiveness and performance of risk management measures implemented throughout the project lifecycle. Additionally, the absence of dedicated PPP

legislation and a unified national regulatory framework has led to inconsistencies in policy implementation across different regions, raising concerns about model applicability. Correspondingly, this study is limited by the selection of case applications, where the validation of the proposed fuzzy comprehensive risk evaluation model should be further tested using empirical data from diverse PPP projects across various cities and regions. With regard to the issue, future studies could apply the FCRE model to the risk evaluation of a wider range of relevant CMTPPs. Apart from that, the interrelationships and interactions among risk indicators are also worth exploring in depth, which could provide a more insightful and holistic perspectives on the risk management strategies of CMTPPs.

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Appendix

Appendix A: The cross-reference table integrating 32 risk factors and the sources of literature for identifying risk factors (Risk factors are expressed as indicator codes).

NO	Risk Factors	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A1	B1	C1	D1	E1	F1	G1	H1	SUM
1	C1-1	√	√	√					√																											4
2	C3-1				√	√	√	√	√		√						√		√								√									9
3	C3-2						√	√									√																		√	4
4	C1-6							√	√	√																										3
5	C1-2										√	√	√																							3
6	C1-4								√												√														√	3
7	C1-5	√							√																										√	3
8	C4-1	√												√	√																					3
9	C4-2					√			√					√		√																				4
10	C4-3						√				√						√	√	√	√				√												7
11	C2-2								√					√		√			√	√						√										6
12	C2-3								√							√			√																	3
13	C5-1								√										√		√															3
14	C6-2					√	√		√																											3
15	C3-3						√									√			√																	3
16	C7-1																				√	√	√											√		4
17	C7-2	√					√		√										√																	4
18	C5-2						√												√					√												3
19	C9-2								√							√											√									3
20	C8-2						√									√												√								3
21	C9-1						√																	√					√							3
22	C9-5	√							√																					√						3
23	C9-4						√		√					√		√			√		√															6
24	C9-6								√						√																				√	3
25	C10-1								√							√			√																	3
26	C10-2						√									√			√																	3
27	C10-4													√	√																					2
28	C10-5					√			√									√																		3
29	C11-1								√										√																	2
30	C11-2								√							√			√																	3
31	C7-3	√							√																								√			3
32	C9-9																		√														√			2

Note. Literature sources for identifying each risk factor are indicated in the table by alphabetical codes, a total of 34 publications, coded A to Z and A1 to H1, respectively.

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