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Research on risk sharing and benefit evaluation of construction project cost management under PPP mode

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Abstract: Traditional cost management focuses on cost control in the construction stage, ignoring the dynamic evolution of risk and comprehensive evaluation of benefits in the whole life cycle, leading to project cost overruns and frequent disputes. Based on the whole life cycle perspective, combined with game theory and incomplete contract theory, this paper systematically studies the risk sharing and benefit evaluation mechanism of construction project cost management under PPP (Public-Private Partnership) mode. Firstly, the whole life cycle risk of PPP project is identified by WBS-RBS method and Delphi method, and the fuzzy mathematics theory is used for quantitative evaluation. Secondly, a risk sharing model between government and enterprises based on game equilibrium is constructed, and Shapley value is used to calculate the risk cost or compensation that each participant should bear, so as to realize reasonable risk sharing. Finally, the multi-dimensional benefit evaluation index system covering four dimensions of economy, society, sustainability and development is established, and the improved fuzzy comprehensive evaluation method is used for dynamic evaluation to realize the linkage simulation analysis of "risk-benefit". Through the case study, the effectiveness and operability of the risk sharing mechanism and benefit evaluation system are verified, which provides forward-looking decision support for the government and social capital, promotes the transformation of PPP project cost management from "cost control" to "value creation", and helps the high-quality development of infrastructure.

1. Introduction

With the acceleration of global urbanization and the surge in demand for public infrastructure, the traditional government-led investment and financing model faces challenges such as increasing financial pressure and low construction efficiency. In this context, the Public-Private Partnership) model has become the core path to promote the high-quality development of infrastructure with its advantages of risk sharing and benefit sharing [1]. However, PPP projects are characterized by long-term, complexity and uncertainty, and its cost management runs through the whole life cycle of the project (decision-making, financing, construction and operation), involving multi-party interest games such as government, social capital and financial institutions [2-3]. Traditional cost management focuses on cost control in the construction stage, ignoring the dynamic evolution of risk and comprehensive evaluation of benefits in the whole life cycle, which leads to problems such as project cost overruns and frequent disputes [4]. Therefore, how to build a scientific risk sharing mechanism and benefit evaluation system has become a key proposition to improve the efficiency of PPP project cost management.

Based on the whole life cycle perspective, combined with game theory and incomplete contract theory, this paper systematically reveals the dynamic correlation mechanism between risk sharing and benefit evaluation in PPP mode, makes up for the deficiency of isolated analysis of risk and cost in existing research, and enriches the theoretical system of PPP cost management [5]; It is helpful for the government to optimize the franchise agreement, reduce the financial and supply risks, improve the scientific nature of social capital investment decision-making and project sustainability, and promote the transformation of industry cost management from "cost control" to "value creation" to help the high-quality development of infrastructure.

This study solves the problem of "risk-benefit" imbalance in PPP projects, systematically

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identifies the whole life cycle risks, constructs a risk sharing model between government and enterprises based on game equilibrium, and establishes a dynamic benefit evaluation framework of multi-agent collaboration by integrating economic, social and sustainable dimensions. Combined with case comparison and simulation analysis, it puts forward the path of contract optimization and benefit improvement. The research innovatively introduces system dynamics (SD) to simulate the dynamic evolution of risks and benefits, reconstructs the analysis framework from the dual perspective of "life cycle-multi-agent game", and closely follows the policy orientation of PPP in China, and puts forward a landing risk sharing and benefit synergy mechanism.

2. Design of risk sharing mechanism

Firstly, the WBS-RBS (Work Breakdown Structure Risk Breakdown Structure) method combined with expert survey method (Delphi method) is used to divide the entire life cycle of PPP projects into stages such as decision-making, financing, construction, operation, and handover. A matrix of work breakdown structure and risk breakdown structure is constructed to systematically identify potential risk factors in each stage. Through multiple rounds of expert consultation, the risk list is screened, supplemented, and confirmed to ensure the comprehensiveness and accuracy of risk identification [6].

Because many risks are difficult to be described with accurate data, using fuzzy mathematics theory, experts are invited to make a "high, medium and low" fuzzy evaluation on the occurrence probability (P) and the losses (C) caused after the occurrence, and the quantitative P,C is obtained by calculating the defuzzification value.

$$RM = P \times C \tag{1}$$

Among them, RM is the risk quantity, which is used to measure the overall size of risk and is the core basis of risk sharing priority. P is the probability of risk occurrence, which is obtained by expert scoring method or statistical analysis of historical data, and the value range is usually [0,1]. C is the risk consequence, expressed in monetary form or the degree of influence on the key objectives of the project.

The government and social capital are regarded as both sides of the game. For each identified risk, calculate the "alliance benefit" generated when the risk is borne by different subjects (government alone, social capital alone, and shared by both parties) [7-8]. Shapley value calculates the average of the marginal contributions made by all parties in all possible alliance combinations, which is used as the basis for risk cost sharing or income compensation.

$$\varphi_i = \sum_{S \subseteq N \setminus \{i\}} \left[\frac{|S|!(|N|-|S|-1)!}{|N|!} \right] [v(S \cup \{i\}) - v(S)] \tag{2}$$

Calculate the score of each participant, where $\varphi_i(v)$ represents the Shapley value (that is, the risk cost or compensation) of the player i, N is the set of all participants, S is any subset excluding i, $v(S)$ is the benefit function of the alliance S, and $|S|$ is the number of alliance members. The essence of this formula is to calculate the weighted average of the marginal contribution of participant i in all possible alliances, and the weight depends on the scale of the alliance, thus providing a theoretical basis for quantifying the risk sharing ratio in PPP projects.

The SD model is established to simulate the influence of key risk factors on the project cost-benefit with time. Set the trigger mechanism, when the monitored risk variables change beyond the scope agreed in the contract, automatically start the renegotiation procedure, and dynamically adjust the project return mechanism with reference to the initial Shapley value sharing principle to realize risk re-sharing.

3. Construction of benefit evaluation system

Benefit evaluation should go beyond a single financial perspective and build a multi-dimensional comprehensive evaluation system that runs through the whole life cycle (as shown in Table 1). Based on the Balanced Scorecard (BSC) and Pressure State Response (PSR) models, a multidimensional benefit evaluation index system covering the entire lifecycle is constructed to systematically evaluate the performance of PPP projects from four dimensions: economic and financial, social and public, process and management, and sustainable and developmental. The economic and financial dimensions focus on net present value (NPV), return on investment (ROI), life cycle cost (LCC), and cost control rate; Social and public dimensions include public satisfaction, employment-driven, service quality and social stability; The process and management dimensions include time limit for a project achievement rate, quality qualification rate, safety accident rate and contract performance rate; The dimension of sustainability and development focuses on carbon emission reduction, technological innovation and regional economic promotion, forming a comprehensive and multi-angle benefit evaluation framework.

Table 1 Multi-dimensional benefit evaluation index system of whole life cycle

Dimension	Index
Economic and financial dimensions	NPV, ROI, LCC, cost control rate
Social and public dimensions	Public satisfaction, employment-driven effect, service quality and social stability
Process and management dimensions	Time limit for a project achievement rate, quality qualified rate, safety accident rate and contract performance rate
Dimensions of sustainability and development	Contribution of carbon emission reduction, application of technological innovation and promotion of regional economic development

Subjective and objective comprehensive weighting method combining analytic hierarchy process (AHP) and entropy weight method is adopted [9-10]. The subjective weight of each dimension and index is determined by synthesizing expert opinions through AHP method; Then the entropy weight method is used to calculate the objective weight according to the dispersion degree of case data or simulation data. Finally, the subjective and objective weights are weighted and synthesized, and a scientific and reasonable comprehensive weight W_j is obtained, which overcomes the limitation of single weighting.

The improved fuzzy comprehensive evaluation method is used to dynamically evaluate the multi-dimensional benefits of PPP projects. By establishing a comment set V ={ excellent, good, medium and poor}, experts are organized to grade each index according to actual or predicted data, and their membership degrees in different grades are determined, and a fuzzy relation matrix R is constructed to effectively deal with the problems of fuzzy information and strong uncertainty in benefit evaluation, so as to realize the comprehensive quantitative evaluation of multi-dimensional benefits such as economy, society, management and sustainability.

$$B = W \circ R \quad (3)$$

In the above formula, B is the final evaluation result vector, which indicates the membership degree of the project in each evaluation level. W is the comprehensive weight vector. R is a fuzzy evaluation matrix, which is composed of row vectors of membership degree of each index. $\circ$ is a fuzzy synthesis operator. Finally, a comprehensive score can be calculated to visually compare the benefit levels of different projects or different stages.

Embed the above benefit evaluation system into the SD model. In the SD model, key risk factors serve as variables that directly affect economic performance indicators and process management indicators. By simulating different risk scenarios, the change curve of the project benefit evaluation value B over time can be dynamically observed, achieving a linkage simulation analysis of "risk benefit". Provide forward-looking decision-making support for the government and social capital.

4. Empirical research

Taking the PPP project of a sewage treatment plant in an ecological new town of a city as an example, the project adopts the return mechanism of "government payment+feasibility gap subsidy", and the project company is responsible for the investment, financing, design, construction and operation and maintenance during the 20-year cooperation period (including the 2-year construction period), which will be handed over free of charge at the expiration, and the core performance indicators are the sewage treatment capacity and the effluent quality compliance rate; The research data mainly comes from the feasibility study report of the project, the value-for-money evaluation report, the financial affordability demonstration report, the draft contract, and the questionnaire survey and interview with 15 experts from the government, social capital, consulting institutions and universities.

Through WBS-RBS method and Delphi method, 15 core risks in the whole life cycle of the project are identified. Invite experts to use fuzzy language terms (very high, high, medium, low, very low) to evaluate the occurrence probability (P) and loss consequence (C) of each risk, and defuzzify them to get quantitative values. The quantitative results of some core risk factors are shown in Table 2.

Table 2 Quantitative results of some core risk factors

Risk number	Risk factor	Probability of occurrence(P)	Consequence of loss C (million yuan)	Risk quantity RM (million yuan)
R01	Overexpenditure of construction cost	0.65	8000	5200
R02	Insufficient demand for sewage treatment	0.45	12000	5400
R03	Improvement of effluent quality standard	0.30	5000	1500
R04	fluctuations of the interest	0.50	3000	1500
R05	Government payment delay	0.25	2000	500

Taking the risk of insufficient demand for sewage treatment (R02) as an example, the Shapley value of government and social capital is calculated by using the cooperative game model.

The benefit function $v(S)$ is defined. Under this risk, the cost (that is, the avoided loss) that different alliances can save by managing the risk through the optimal strategy. After expert evaluation:

$v(\varnothing)=0$ (No risk, no savings)

v(government) = 30 million yuan (the government can save 30 million losses by dealing with it alone)

v (social capital) = 40 million yuan (social capital alone can save 40 million losses)

v (government, social capital) = 80 million yuan (the two sides can save 80 million losses by cooperating together)

Calculate the Shapley value φ_{gov} of the government:

Contribution of the government to form an alliance alone: v (Government)- $v(\varnothing)$ = 30 million-0 = 30 million yuan

The contribution of the government to the social capital alliance: v (government, social capital)- v (social capital) = 8000-4000 = 40 million yuan

Shapley value is the weighted average of marginal contribution (the weight calculation is abbreviated):

φ_{gov} =(1/2)*3000+(1/2)*4000=3500 million yuan

Similarly, calculate Shapley value s of social capital φ_{spv} :

φ_{spv} =(1/2)*4000+(1/2)*(8000-3000)=4500 million yuan

The total management benefit (cost saving) of this risk is 80 million yuan. According to the principle of fair distribution of Shapley value, the government should bear the risk responsibility corresponding to the benefit of 35 million yuan, and the social capital should bear the responsibility corresponding to 45 million yuan. In practice, this will be translated into contract terms: when the demand is insufficient, the government should bear its share of responsibility of 35 million yuan by increasing the minimum demand guarantee payment, and the remaining 45 million yuan loss risk will be digested by the social capital itself (by optimizing operations, exploring new users, etc.), thus encouraging it to improve efficiency.

Based on the established four dimensions, 12 key indicators are selected and comprehensively weighted by AHP- entropy weight method. See Table 3 for benefit evaluation index system and comprehensive weight.

Table 3 Benefit evaluation index system and comprehensive weight

Dimension	Index	Comprehensive weight(W_j)
Economy and finance (0.40)	1. NPV of the whole life cycle of the project	0.15
	2. Financial internal rate of return on capital	0.10
	3. Annual operating cost saving rate	0.08
	4. Cost control deviation rate	0.07
Society and the public (0.25)	5. Public satisfaction	0.10
	6. Employment-driven effect	0.08
	7. Stable compliance rate of effluent quality.	0.07
Process and management (0.20)	8. Time delay rate	0.07
	9. Number of major safety accidents	0.06
	10. Frequency of contract	0.04

	changes	
Sustainability and development (0.15)	11. Reduction rate of unit energy consumption	0.08
	12. Number of technological innovation applications	0.07

After the fifth year of project operation, the actual data of each index are collected, and the expert group is invited to make fuzzy evaluation according to the predetermined standard, and the fuzzy relationship matrix R is constructed. The fuzzy comprehensive evaluation model $B = W \circ R$ is used for calculation. Finally, the comprehensive evaluation value vector is obtained:

B=(0.52,0.31,0.12,0.05)

That is to say, in the fifth year of the project operation period, the degree of the benefit level belonging to "excellent" is 52%, "good" is 31%, "medium" is 12% and "poor" is 5%.

The project performed well in economic, financial and process management dimensions, which benefited from effective risk sharing. The social public dimension performed well, but the score of sustainability dimension was relatively low, indicating that there is still room for improvement in energy conservation, emission reduction and technological innovation. This points out the direction for the project company to optimize its operation in the next step.

The risk sharing mechanism and benefit evaluation system constructed are operable and effective in practical projects. The risk sharing model based on game theory can draw a fairer and more efficient scheme than traditional empirical negotiation, and significantly improve the project benefits. SD simulation provides a forward-looking dynamic perspective for contract design and decision-making, and helps to formulate more flexible contract terms. It is suggested that Shapley value risk sharing principle and dynamic adjustment trigger mechanism proposed in this study should be adopted in the mid-term evaluation of this project and future contracts of similar projects, and the multi-dimensional benefit evaluation results should be linked with the government's performance payment to achieve real incentive compatibility.

5. Conclusion

The proposed risk sharing mechanism and benefit evaluation system are operable and effective in practical projects. Through case analysis, it is verified that the risk sharing principle based on Shapley value can significantly improve the project benefit, and SD simulation model provides a forward-looking dynamic perspective for contract design and decision-making, which is helpful to formulate more flexible contract terms. In addition, the multi-dimensional benefit evaluation results are linked with the government's performance payment, realizing real incentive compatibility. This study provides a scientific risk sharing and benefit evaluation framework for construction project cost management under PPP mode, which helps the government to optimize franchise agreements, reduce financial and supply risks, enhance the scientificity of social capital investment decision-making and project sustainability, promote the transformation of industry cost management from "cost control" to "value creation", and help the high-quality development of infrastructure.

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