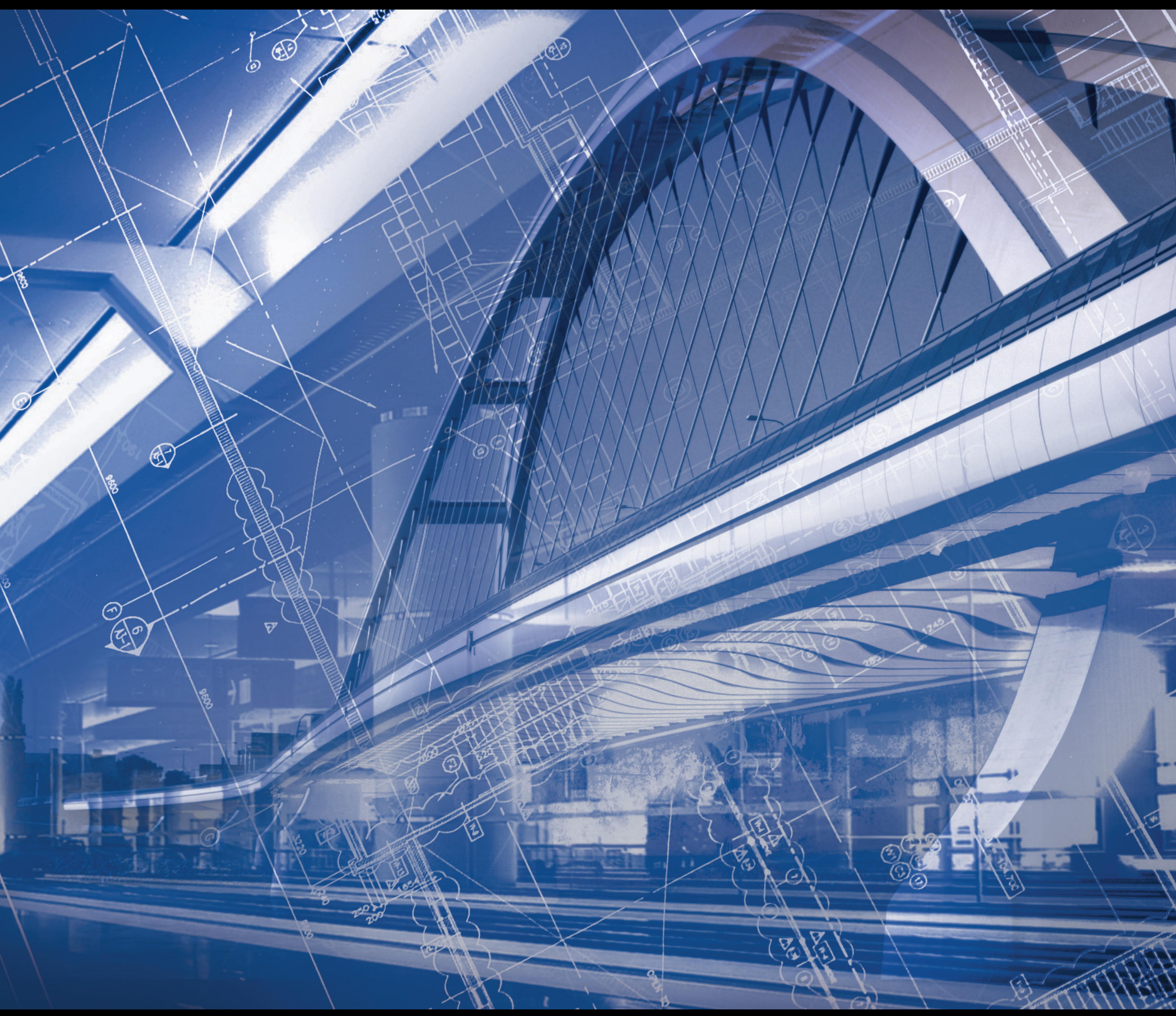
Advances in Civil Engineering

Advanced Management in Civil Engineering Projects

Special Issue Editor in Chief: Xianbo Zhao
Guest Editors: Yingbin Feng, Dujuan Yang, and Dong Zhao



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Editorial Board

Contents

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Editorial

Advanced Management in Civil Engineering Projects

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This special issue aims to present the research studies regarding management in civil engineering projects, which provide theoretical and/or practical implications. Over eighty manuscripts were submitted, and 29 were accepted for publication after a thorough and rigorous peer review process. These papers cover a variety of topics in management of civil engineering projects, including risk and safety management, public-private partnership (PPP), human factors, information technology applications, construction organizational issues, planning and scheduling, and sustainability and resilience of civil infrastructures. We believe that the original papers in this special issue cover the hot topics in construction management research and will bring readers the latest advances in the field.

The paper by T. Ganbat et al. presents a bibliometric review of risk management and building information modeling (BIM) for international construction. The paper by T. Chang et al. models the paths of political risks in the international construction market and develops relevant strategies to mitigate these risks.

The paper by S. Xu et al. explores the impact examining whether attitudinal ambivalence is a mediating factor in the relationship between safety attitude and safety behavior. The paper by Y. Li et al. identifies the critical success factors (CSFs) for safety management of high-rise building construction projects and explores the interactions among such CSFs. The paper by T. Zhao et al. analyzes the status quo of safety management and identifies the “last mile” problem, i.e., the failure of implementation of the extensive legal and regulatory systems on the construction site.

The paper by Y. Liu et al. adopts case studies to identify the risk factors affecting PPP waste-to-energy incineration projects in China. The paper by Y. Liang et al. constructs key success indicators for PPP projects in Hong Kong. The paper by J. Li et al. uses the risk management approach to analyze the traffic allocation mode of PPP highway projects.

The paper by G. Ye et al. develops an improved Human Factors Analysis and Classification System (I-HFACS) in the construction industry and designs an analytical I-HFACS mechanism to interpret how activities and decisions made by upper management lead to operator errors and subsequent accidents. The paper by P.-C. Liao et al. proposes a model for identifying, analyzing, and quantifying the mechanisms for the influence of an improper workplace environment on human errors in elevator installation.

The paper by Z. Xu et al. extends the interoperability of a construction quality database in the evaluation process by employing the industry foundation classes (IFCs) data model. The paper by T.-K. Wang et al. quantitatively assesses the efficiency of augmented reality (AR) from the cognitive perspective in the context of construction education and compares learners’ visual behaviors in text-graph- (TG-) based, AR-based, and physical model- (PM-) based learning environments.

The paper by Y.-H. Lin et al. explores the moderating effect of guanxi on the dynamic capacity and competitive advantage of international contractors. The paper by G. Wu et al. takes into consideration the effects of the contractor’s conflict behaviors on the project benefit and develops a decision model between the owner and contractor’s conflict behaviors in construction projects using the principal-agent theory and game theory. The paper by P. Yan et al. investigates the potential individual, group, and organizational factors that influence group bidding decision-making for construction projects.

The paper by J. Dong et al. develops a network planning method for the capacitated metro-based underground logistics system (ULS) and validates this method using two lines of Nanjing Metro. The paper by M. Kannimuthu et al. determines the most challenging issues being faced in handling the multiproject environment, enumerates the practices adopted in the industry, and identifies the practitioners' perceptions on the multiproject scheduling aspects.

The paper by Y. Liu et al. performs a thorough literature review to follow the development trends, interviews with professionals from the academia and industry, and a critical analysis of technical requirements for integrating BIM tools and infrastructure sustainability rating systems in the design process and develops a conceptual framework for integrating sustainability rating systems by introducing BIM with a sustainability metric plug-in. The paper by L. Wang et al. assesses the sustainability and resilience of the urban infrastructure by adopting the grade point average (GPA) as a unified assessment approach.

Conflicts of Interest

The editors declare that they have no conflicts of interest.

Acknowledgments

We would like to thank all the authors who contributed to this special issue. This publication would not be possible without the participation of our expert reviewers, who provided constructive feedback and criticism throughout the review process.

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Research Article

Valuation of Guaranteed Maximum Price Contracts in Korea Using the Collar Option Model

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This study assessed the levels of risk that contractors may be subject to while executing a GMP contract by applying a collar option model to the case study of an apartment project in Korea and identified implications for the application of GMP contracts in Korea. The payoff structure of the GMP contract was defined based on the collar option model and a profit sharing ratio calculated to evaluate the risks involved in GMP contracts. The results showed that an increase in the GMP and a decrease in the expected cost and cost range were accompanied by a decrease in the profit sharing ratio. The proposed valuation model for GMP contracts is expected to help clients and contractors in Korea negotiate reasonable contracts as it enables the contractor to utilize the proposed model as basic data, the client to evaluate the performance of the contractor, and both parties to agree a reasonable profit sharing ratio. Implementing GMP contracts with CMR is likely to have a number of positive effects on the Korean construction market. However, in order to maximize these effects, it is necessary to have the ability to evaluate cost uncertainty. Accordingly, it is very important to analyze the factors that influence cost volatility. In future work, the various factors that have an impact on the GMP must be studied to maximize the positive effects of the framework proposed in this paper. An analysis of the effect of each factor on the change in the GMP will help Korean construction companies who are attempting to introduce GMP contracts to perform their preconstruction services effectively.

1. Introduction

In Korea, most public projects use the DBB project delivery system. However, according to a Ministry of Land, Infrastructure and Transport (MOLIT), such public projects often fail to identify all the construction risks during the design phase, leading to problems such as frequent design changes, cost overruns, time delays, and legal disputes. In addition, under the traditional fixed-price lump-sum contract, public projects have long suffered from limited trust among the contracting parties, lack of incentives, and misalignment of objectives, all of which tend to result in a confrontational working culture and lead to unfavorable project performance [1]. There is also a tendency to award contracts to the lowest bidders, which more often than not results in low profit margins, so consultants and contractors have little incentive to go beyond the minimum contractual requirements [2].

Korea's MOLIT is seeking to address the above-mentioned problems by introducing a new approach, construction management at risk (CMR), into public projects. CMR emphasizes cooperation between the contracting parties, with the construction manager being in charge of the overall project execution and managing the design and construction contracts. Here, the construction manager is responsible for engaging in a designer consultation process that produces an optimal design that comprehensively considers both cost and schedule. In addition, the construction manager at risk must ensure that the entire construction process satisfies the owner's requirements concerning various aspects of the project, including the cost and schedule, while simultaneously staying within the guaranteed maximum price (GMP) [3–5].

In particular, a GMP contract is significant in terms of risk management, as this approach was originally introduced as an alternative integrated form of procurement to enable clients to minimize risk and integrate the diverse elements of a complex construction project [6]. GMP is a combination of a cost reimbursement contract and an option-like clause [7]. As an incentive-based procurement strategy, it rewards the contractor for any savings made against the GMP and penalizes him when this sum is exceeded because of his own mismanagement or negligence according to a preagreed share ratio [8]. This means that setting the GMP is a crucial step as the risk of cost overruns is entirely shouldered by the contractor. Particularly in Korea, where CMR is being introduced into public projects for the first time, identifying the predictable risk level of a contract is crucial for a reasonable GMP contract.

This study assessed the levels of risk that contractors may be subject to while executing a GMP contract by applying a collar option model to the case study of an apartment project in Korea and identified implications for the application of GMP contracts in Korea.

2. Literature Review

Design-Bid-Build (DBB), Design-Build (DB), and Construction Management at Risk (CMR) are the most general types of project delivery systems. Among these, DBB is the project delivery system traditionally used, with both DB and CMR being actively adopted as alternative systems designed to overcome the drawbacks of DBB. The increasing popularity of DB and CMR has encouraged the use of GMP contracts. Following this trend, several studies have conducted comprehensive examinations of the effects and/or practical implications of GMP contracts. Rojas et al. (2008) compared the cost growth performance of CMR and DBB in public school projects in the Pacific Northwest in the United States, finding that the school project costs exceeded the GMP in 75% of the cases they examined. This demonstrates the difficulties involved in determining a realistic GMP for such projects [9]. Bogus et al. analyzed contract payment provisions and project performance in the water and wastewater industry, reporting that implementing GMP yielded better performance in terms of both cost control and schedule growth [10].

Multiple participants collaborate in the planning/design process during the preconstruction phase, in the course of which the GMP is continuously reestimated. This means that an efficient cooperation system is crucial to minimize the difference between the GMP and the actual project cost. Several previous studies have emphasized the importance of effective partnerships between the contracting parties. For example, Bresnen and Marshall explored partnerships and related forms of collaboration in the UK construction industry and investigated the economic, organizational, and technical factors that encourage or inhibit collaboration between contracting partners [11]. Walker et al. clarified the nature of project alliances and discussed how alliance member organizations are selected [12]. Hauck et al. determined the extent to which the National Museum of Australia project was able to effectively incorporate the theoretical underpinnings of the collaborative process [13].

Since effective cooperation between the various parties of a GMP contract can increase the owner's profit, several studies have also examined an additional profit structure. Broome and Perry investigated how different sharing fractions are established for cost over- or underruns and how these fractions can vary depending on the degree of the cost over- or underruns compared with the target. They showed that utility theory alone is insufficient to deal with the complex interactions among the factors that govern the choice of the share profile [14]. Badenfelt sought to provide a broader understanding of target cost arrangements via an empirical study of the choice of sharing ratios from the perspective of both clients and contractors [15], while Rose and Manley provided a set of recommendations for construction clients who design and implement financial incentive mechanisms in projects [16]. Boukendour and Bah defined a GMP contract as a combination of a cost reimbursement contract and an option-like clause and examined how the option pricing model must be adapted in order to estimate the value of the GMP clause as a call option [7].

All the abovementioned studies examined the specific characteristics of a GMP contract and highlighted the importance of setting a reasonable GMP. A GMP contract represents a measure of risk management and provides insurance against the uncertainty of cost overruns for the client, while the contractor is responsible for the risk of cost overruns. Rojas et al. (2008) found that in reality, the construction cost often exceeds the GMP even in the US, where CMR is more actively implemented [9]. In Korea, where implementing CMR in public projects is in its infancy, it is very important to assess the level of risk transfer in a GMP contract and identity the related implications.

3. Research Methodology

This study utilized a collar option model to create a valuation capable of addressing the structural properties of a GMP contract appropriately. An option is a security giving the right to buy or sell an asset, subject to certain conditions, within a specified period of time [17]. An option is a right, but not an obligation, to take an action in the future. In financial markets, the most common types of options are a call option and a put option. A call option gives the owner the right to buy a stock at a predetermined exercise price on a specified maturity date. A put option can be viewed as the opposite of a call option. A put option gives its owner the right to sell the stock at a fixed exercise price. Stock prices are notorious for their volatility [18].

A collar option is a more complex arrangement as it effectively combines the call and put options [19]. A popular type of collar is the zero cost collar. Typically, the proceeds from the sale of the call are used to offset the cost of the put, which eliminates the cost of the hedging instrument. The put provides the holder with insurance to protect against any downward movement in the stock price below the exercise price. Any movement above the exercise price of the call represents lost profit [20].

In addition to clauses in the general service agreement between the owner and contractor, a GMP contract includes an optional clause related to cost variation. Here, either an incentive or a penalty is imposed on the contractor according to the construction cost based on the GMP. Incorporating such a payoff structure in a GMP contract can thus be conveniently explained by the collar option model.

3.1. Framework for Valuing a GMP Contract Using a Collar Option Model. The CMR process can be divided into the preconstruction phase and the construction phase. Figure 1 shows how in the preconstruction phase, the general contractor improves the accuracy of the initially determined GMP by providing various services. Hence, the initial GMP ($\mathrm{GMP_i}$) develops into the final GMP ($\mathrm{GMP_{fix}}$) as a result of these preconstruction services. $\mathrm{GMP_{fix}}$ can vary according to the design quality and preconstruction services and may also differ from the final cost ($\mathrm{Cost_A}$) incurred in the actual construction phase as a result of cost uncertainty. Although $\mathrm{GMP_i}$ has the greatest variability in terms of cost volatility, this variability is decreased by the performance of various preconstruction services designed to determine $\mathrm{GMP_{fix}}$ more accurately. If the preconstruction services are ineffective, the variability of GMP does not decrease, and thus α and β in Figure 1 become equivalent. In this regard, $\mathrm{GMP_i}$ may be considered as one case of $\mathrm{GMP_{fix}}$. On the contrary, if the preconstruction services are effective, the difference between α and β will increase. In addition, the uncertainty during the construction phase is considered in the variation section of $\mathrm{GMP_{fix}}$, which includes $\mathrm{Cost_A}$.

Since Korea is only in the initial stages of introducing CMR and thus lacks extensive experience in its implementation, the data needed to establish realistic risk valuations for GMP contracts have not yet been sufficiently established. This paper attempts to overcome this lack of basic data by assuming that DBB is the worst case of a CMR delivery system, where the preconstruction services are minimal at best. As better preconstruction services are applied, the cost uncertainty improves, and GMP is reestimated. Thus, if a change in the value of the GMP contract due to some variation in the variables can be identified, the risk transfer level of the GMP contract can be assessed more effectively.

A GMP contract has an unusual payoff structure as it includes not only construction costs but also a contingency fund and the contractor's fee. Figure 2 shows how the payoff structure of a GMP contract is configured. In reality, a contractor loss does not always occur when the actual cost exceeds the expected cost incorporated in the GMP: only when the actual cost exceeds, not only the expected cost but also the contingency and contract fee included in the GMP does the contractor suffer a loss. On the contrary, if the actual cost comes in considerably lower than the expected cost, a clause is included that specifies how any such profit is to be shared.

In this respect, the payoff structure of a GMP contract based on cost variation can be schematically represented using the collar option model, as shown in Figure 3 As is clear from the figure, the underlying asset is defined as the cost. The collar option model basically comprises a section allowing the owner to exercise their call option owing to cost increases (Section A), a section for exercising the contractor's put option owing to a cost decrease (Section B), and a neutral section (Section C).

Here, the exercise price (X_c) of the call option is defined as GMP. As noted above, GMP actually includes not only an expected cost estimated at the time of signing the contract but also the contingency fund and the contractor's profit margin. Accordingly, even if the actual cost exceeds the expected cost, the contractor's loss does not immediately occur but is covered by the contingency and profit margin. In other words, since the GMP corresponds to the point where any increase in the cost generates a loss for the contractor, the exercise price (X_c) of the call option is the GMP.

The exercise price (X_p) of a put option is defined as the expected cost. Hence, when the actual cost is below the expected cost, this cost saving immediately generates a profit. Therefore, it is reasonable to set the exercise price (X_p) of the put option to be the expected cost. As the underlying asset (S_o) is the cost estimated at the time of signing the GMP contract, it is defined as the expected cost. Consequently, the exercise price (X_p) of the put option is conceptually the same as the price of the underlying asset (S_o).

Overall, as shown in Figure 3, the owner secures a call option where GMP is the exercise price (X_c), while the contractor secures a put option where the expected cost is the exercise price (X_p). It is reasonable for the GMP contract to place the same value on the optional clauses for the guarantee and profit options. When the GMP and expected cost are determined by agreement between the owner and contractor, the value of the guarantee held by the owner is determined. Consequently, if the value of the profit option in Section B, estimated from Equation (1) below, is adjusted by the profit sharing ratio (K), which corresponds to the slope, the value of the guarantee secured by the owner and the incentive value of the contractor can be calculated identically. A relative increase in K effectively indicates that the value of the guarantee obtained by the owner occupies a high proportion of the value of the profit option. As this signifies a relative increase in the effect of the guarantee, it can be inferred that the owner transfers more risk to the contractor.

$$
\begin{aligned}
\mathrm{Value_{guarantee}} &= \mathrm{Value_{profit\ option}} \times K, \\
\mathrm{Value_{profit\ option}}&: \text{ value of profit option}, \\
\mathrm{Value_{guarantee}}&: \text{ value of guarantee}, \\
K&: \text{ Profit sharing ratio}.
\end{aligned}
\tag{1}
$$

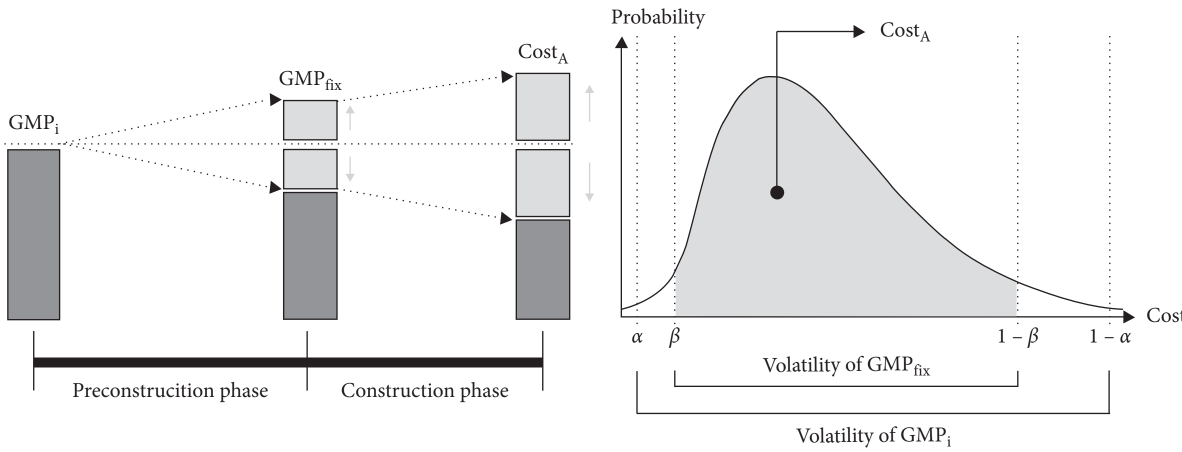

Figure 1: Uncertainty of Cost$_A$ (actual cost) in the GMP contract.

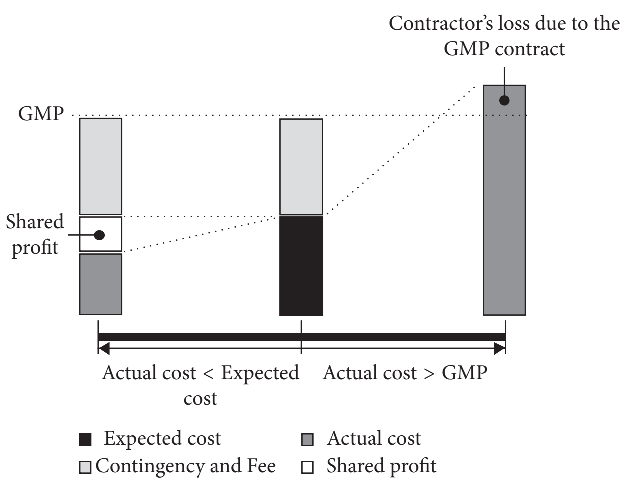

Figure 2: Payoff structure of the GMP contract.

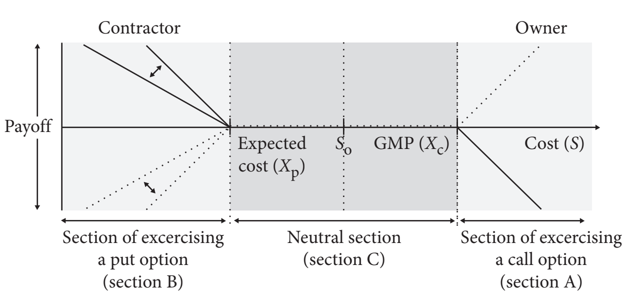

Figure 3: Valuation of the GMP contract based on the collar option model.

3.2. Binomial Lattice Model for Calculating Option Value. Cox et al. proposed the use of a binomial lattice model to calculate option values under the assumption that any change in the underlying asset will have a binomial distribution. The binomial lattice model can solve complex and realistic option pricing problems [21]. The model consists of two processes: one is the forward process, where the binomial tree of the distribution of the underlying asset is configured as shown in Figure 4, the other is the backward process, where the binomial tree for calculating the option value is configured as shown in Figure 5 [22].

In the first step, the underlying asset (S) must be determined in the binominal tree. As shown in Figure 3, the value of the GMP contract varies according to changes in the cost. Accordingly, the present value of the expected cost of a project is defined as the underlying asset (S). The binomial tree formed by the forward process can be considered a process in which the cost may change over time owing to uncertainty. In this regard, the binomial tree in Figure 4 repeatedly calculates the rise rates (u) and the fall rates (d) of the underlying asset (S), both of which depend on the volatility of the underlying asset. However, if the maximum and minimum values of the underlying asset (S) can be identified at the final point, the probabilities can be calculated by the following Equations [23].

$$u = \sqrt[t]{\frac{S_{u^t}}{S_o}}, \tag{2}$$

$$d = \sqrt[t]{\frac{S_{d^t}}{S_o}}, \tag{3}$$

where t = construction period, S_{u^t} = maximum expected cost at the final point (t), and S_{d^t} = minimum expected cost at the final point (t).

Based on the binomial tree completed by the forward process, the backward process calculates the option value. The binomial tree in Figure 5 presents the iterative calculation process where the option value of each node is obtained by the equation of the final point, and then Equation (4) is used to calculate the value of the present node. At the same time, the risk-neutral probabilities (p) are obtained from Equation (5). In summary, the binomial lattice model is used here to calculate the values of the guarantee and incentives and then the profit sharing ratio determined by applying Equation (1).

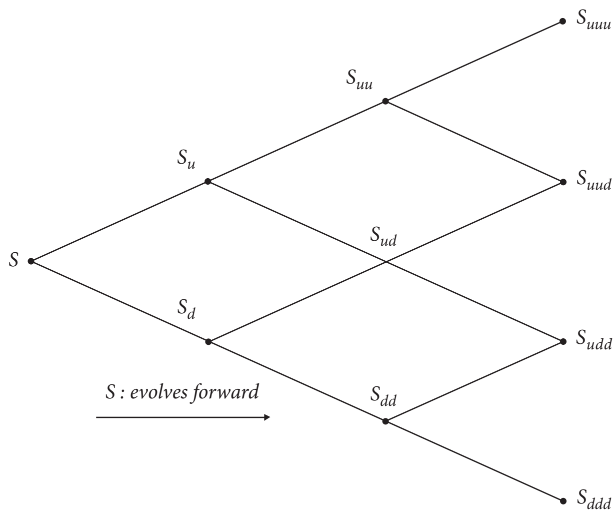

Figure 4: Binomial tree for the underlying asset distribution (forward process).

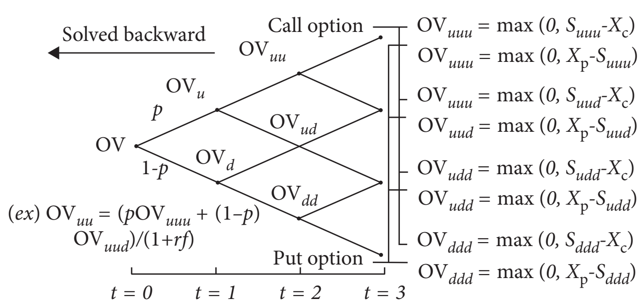

Figure 5: Binomial tree for solving the option value (backward process).

$$OV_{uu} = \frac{pOV_{uuu} + (1-p)OV_{uud}}{1 + rf_{\text{month}}}, \tag{4}$$

$$rf = p \times (u - 1) + (1 - p) \times (d - 1), \tag{5}$$

where rf = risk-free rate, p = risk-neutral probabilities, u = rise rates, and d = fall rates.

3.3. Approach for Setting the Maximum and Minimum Expected Costs. As noted earlier, the maximum and minimum values of the expected cost are needed to calculate the rise (u) and fall (d) rates of the binomial tree. To this end, 18,090 cases of cost changes from 331 apartment house projects, all in Korea, were utilized. The basic information of sample projects is as shown in Table 1 below.

As shown by the sample projects in Table 2, the cost reduction represented only 14.2% of the total, with the great majority, 85.5%, experiencing cost increases, which indicates a very high likelihood of cost overruns. However, in both cases, a very high proportion (72.5%) of the cost variation ratios was within 5%, with only 6.9% exceeding 20%.

Table 1: Basic information of sample projects.

Category	Classification	Project number (%)
Owner type	Public	331 (100.0)
	Private	0 (0.0)
Project type	Residential	331 (100.0)
	Nonresidential	0 (0.0)
G.F.A (m^2)	~50,000	132 (39.88)
	50,000~100,000	158 (47.73)
	100,000~150,000	30 (9.06)
	150,000~200,000	10 (3.02)
	200,000~	1 (0.30)
Project period (month)	~20	31 (9.37)
	20~30	273 (82.48)
	30~40	25 (7.55)
	40~	2 (0.60)

Based on the cost variation data for the sample projects, the frequency and severity distributions were derived. Frequency indicates the number of occurrences of cost change, and severity is defined as the cost variation ratio when cost changes occur. The expected cost distribution was determined by a Monte Carlo simulation using the frequency and severity distributions. Finally, the maximum and minimum expected costs were calculated based on the expected cost distribution.

3.4. Case Study of Valuing a GMP Contract Based on the Collar Option Model. An apartment house project that employed DBB was used for the case study presented here to assess the real-world performance of a GMP contract in Korea. As noted above, DBB is assumed to be the worst case, where the preconstruction service of the CMR delivery system is minimally applied, and the uncertainty of the construction cost is at its greatest.

As shown in Table 3, the apartment house project had a gross floor area of 51,861 m^2 and lasted for 2 years. The expected cost of the project was \$47,756,721, and the GMP was set to \$51,157,000 to reflect the contingency and contract fee. Table 2 provides an overview of the project. The process rate is 43% at the first year and 57% at the second year.

Table 4 presents the main factors used to evaluate the option value inherent in the GMP contract for the apartment house project. The expiration period of the case was 2 years, which corresponds to the construction period, and the time step was calculated to be 1 year. The risk-free rate was set at 2.349%, which was the average interest rate of 5-year public bonds at the time the project commenced. The underlying asset served as the starting point for calculating various estimates of the construction cost and reflected the volatility related to uncertainty. The present value of the underlying asset was then calculated by distributing the expected cost at the time of signing the contract across each time period in accordance with the process rate and applying a discount rate. The discount rate was calculated by adding the average annual inflation rate (1.300%) for the previous 5 years and the above risk-free rate (2.349%). Consequently, the underlying asset (S) was determined to be \$45,150,831.

Table 2: Cost variation ratios of sample projects.

Cost variation ratio (%)	Project number (%)		Average contract amount ($ thousand)	Average final amount ($ thousand)
Total	331	(100.0)	33,348	37,726
−5–0	47	(14.2)	32,233	32,040
0–5	193	(58.3)	30,123	30,749
5–10	42	(12.7)	42,106	45,263
10–15	26	(7.9)	41,303	46,974
15–20	16	(4.8)	38,854	46,906
20–25	7	(2.1)	36,687	46,848

Table 3: Project overview.

Category	Item	Details
Basic information	Construction period	2 years
	Number of floors	A basement and a 20-floor building
	Number of households	394 households (5 apartment blocks)
	Structure	Reinforced concrete
	Gross floor area	51,861 m^2
GMP	Expected cost	$47,756,721
	Contingency	$1,432,702
	Contract fee	$1,967,577
	Total	$51,157,000
Progress rate	t = 1	43%
	t = 2	57%

Table 4: Valuables used for calculating option value.

Variables	Estimated value
Underlying asset (S)	$45,150,831
Exercise price of call option (X_c)	$51,959,689
Exercise price of put option (X_p)	$48,506,057
S_{max}	$62,074,638
S_{min}	$42,934,102
Risk-free rate (r_f)	2.349%
Time interval	1 year
Rise rates (u)	1.1725
Fall rates (d)	0.9751
Risk-neutral probability (p)	0.2449

The exercise price (X_c) of the call option in Section A, where the owner gains the value of the guarantee, was calculated to be $51,959,689, which was hence the future price for GMP. In addition, the exercise price (X_p) of the put option in Section C, where the value of the profit option is taken into account, was calculated to be $48,506,057, which was the future price of the expected cost.

As explained earlier, the maximum and minimum values of the underlying asset (S) must be calculated to determine the rise and fall rates. Therefore, multiple cost change data were utilized to implement the Monte Carlo simulation, which resulted in the distribution.

Based on the simulation results, Table 5 shows the maximum and minimum values of the cost according to the volatility ranges. As the analysis of this case assumes that the failure to apply preconstruction services in the CMR delivery system is the worst case, this has the greatest uncertainty. Accordingly, since the largest range of cost to be applied for valuing the GMP contract is 0.05–99.95%, the maximum and minimum values of cost were calculated to be $62,074,638 and $42,934,102, respectively. These values were used to determine the rise rate, the fall rate, and the risk-neutral probability by applying Equations (2), (3), and (5), respectively.

Table 5: Maximum and minimum values of cost.

Range	Maximum value	Minimum value
0.05–99.95% (0.1%)	$62,074,638	$42,934,102
0.5–99.5 (1%)	$57,901,101	$44,945,033
2.5–97.5 (5%)	$55,190,504	$46,359,045
5–95 (10%)	$54,070,058	$46,819,569
7.5–92.5 (15%)	$53,414,426	$47,110,991

The variables in Table 4 were employed in the forward process to obtain the various probable values of the underlying asset. Based on the basic binomial lattice model produced by the forward process, the backward process for the call option model was applied to calculate the value of the guarantee obtained by the owner, and the value of the guarantee was $579,289. Next, the value of the profit option was calculated by applying the backward process for the put option model, and the value of the profit option was $3,032,565. As the value of the guarantee obtained by the owner should be the same as the incentive that the contractor could potentially obtain, a sharing ratio for the distribution of the value of the entire profit option was then calculated. Thus, Equation (1) was used to obtain a profit sharing ratio of 19.1%, as presented in Table 6.

Table 7 shows the variation in the K-ratio according to the GMP, the expected cost, and thus the cost range, and analyzes the risk transfer level of the GMP contract. In

Table 6: Profit sharing ratio.

Category	Estimated value
Value of guarantee	$579,289
Value of profit option	$3,032,565
Profit sharing ratio	19.1%

Table 7: Fluctuation of *K*-ratio under various conditions.

GMP (million $)	Range (%)	Expected cost (million $)				
		50.0	50.5	51.0	51.5	52.0
52.0	0.05–99.95	0.391	0.460	0.524	0.566	0.609
	0.50–99.50	0.295	0.354	0.403	0.455	0.512
	2.50–97.50	0.173	0.216	0.265	0.321	0.388
	5.00–95.00	0.104	0.138	0.177	0.226	0.289
	7.50–92.50	0.055	0.075	0.101	0.135	0.183
52.5	0.05–99.95	0.369	0.434	0.496	0.535	0.575
	0.50–99.50	0.265	0.319	0.363	0.410	0.461
	2.50–97.50	0.136	0.170	0.208	0.252	0.305
	5.00–95.00	0.062	0.082	0.105	0.134	0.172
	7.50–92.50	0.008	0.011	0.015	0.020	0.028
53.0	0.05–99.95	0.348	0.409	0.467	0.504	0.542
	0.50–99.50	0.236	0.284	0.322	0.364	0.410
	2.50–97.50	0.099	0.124	0.151	0.183	0.222
	5.00–95.00	0.020	0.026	0.034	0.043	0.055
	7.50–92.50	0.000	0.000	0.000	0.000	0.000
53.5	0.05–99.95	0.326	0.384	0.438	0.472	0.509
	0.50–99.50	0.206	0.248	0.282	0.319	0.359
	2.50–97.50	0.062	0.077	0.095	0.115	0.139
	5.00–95.00	0.000	0.000	0.000	0.000	0.000
	7.50–92.50	0.000	0.000	0.000	0.000	0.000
54.0	0.05–99.95	0.305	0.359	0.409	0.441	0.475
	0.50–99.50	0.177	0.213	0.242	0.273	0.308
	2.50–97.50	0.025	0.031	0.038	0.046	0.056
	5.00–95.00	0.000	0.000	0.000	0.000	0.000
	7.50–92.50	0.000	0.000	0.000	0.000	0.000

addition, based on the results shown in Table 7, Figures 6 and 7 present the schematic graphs of the *K*-ratio with one variable fixed and the remaining variables changeable.

In Figure 6, the increase in the GMP is accompanied by a decrease in the *K*-ratio. The increase in the GMP with a fixed expected cost indicates an increase in either the contingency or contract fee. As this again indicates an increase in the buffer within which the contractor can react to cost overruns, the actual cost becomes less likely to exceed the GMP. Thus, when GMP increases, the *K*-ratio decreases. On the contrary, Figure 7 shows that an increase in the expected cost is accompanied by an increase in the *K*-ratio. The increase in the expected cost with a fixed GMP indicates a decrease in either the contingency or contract fee. Hence, as the actual cost becomes more likely to exceed the GMP, the *K*-ratio increases. Interestingly, a decrease in the cost range was accompanied by a decrease in the *K*-ratio. As the accuracy of cost estimation is high, a decrease in the cost range means that there must be a relative reduction in the actual cost uncertainty. Thus, when the cost range decreases, the *K*-ratio also decreases.

Table 7 has been constructed based on the proposed valuation model used for the GMP contract. In a Korean

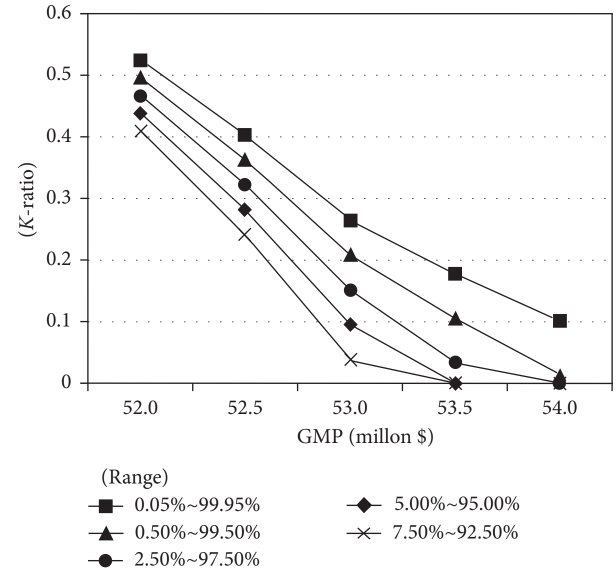

Figure 6: *K*-ratio at expected cost of $51 (million).

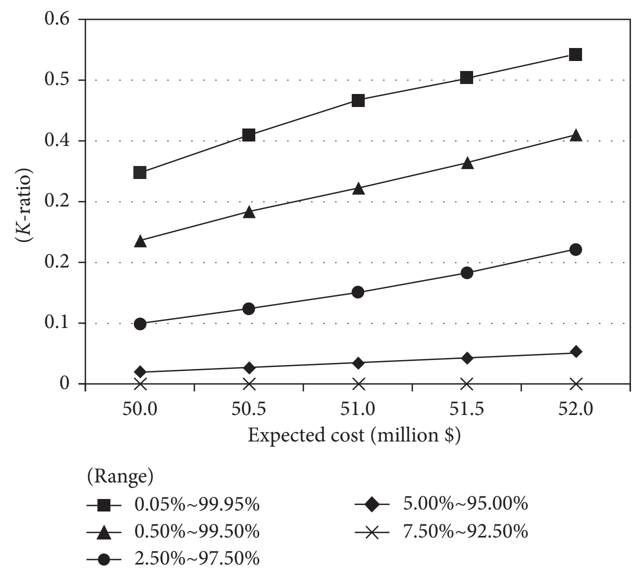

Figure 7: *K*-ratio at GMP of $53 (million).

context, this table may help owners and contractors execute GMP contracts in a reasonable manner. If contractors continue to perform projects based on GMP contracts, they will be able to calculate the probability distribution of the accuracy when estimating the construction cost by using their own preconstruction services. Since such a probability distribution can ultimately be defined as the cost range, the valuation model used in this paper may help the contractor calculate a reasonable contingency fund and fee margin and thus determine the GMP. When making a GMP contract, the owner can utilize the proposed framework to determine a reasonable level of incentive according to the expected cost and GMP. A public ordering organization can accumulate performance data for the companies tendering for a project based on their track record from various projects and assess their performance using the data. Furthermore, as the accuracy of the GMP for each company is refined based on the valuation data, the organization will be able to effectively discuss the GMP or *K*-ratio with each tendering company in future projects.

4. Discussion and Conclusion

This study assessed the levels of risk that contractors may be subject to while executing a GMP contract by applying a collar option model to the case study of an apartment project in Korea and identified implications for the application of GMP contracts in Korea.

The framework proposed in this paper can be applied to evaluate a GMP contract, as it utilizes an established DBB project in the initial stage of CMR implementation. The framework can also apply the collar option model to analyze the unique payoff structure of a GMP contract and utilize the results of the analysis as an effective valuation tool. Finally, the framework can be utilized to set a reasonable profit sharing ratio and then apply this to assess the contractor's risk level. In other words, the valuation model allows owners and the general contractors to provide useful information in decision-making of GMP contract. Utilizing the analysis results, owners and general contractors can discuss reasonable GMP, profit sharing ratio. By confirming the risk transfer level based on the change of *K*-ratio, the contracting parties can effectively evaluate a reasonable contingency fund and fee margin.

The analysis results showed that an increase in the cost uncertainty is accompanied by an increase in the risk level of a GMP contract. This means that an increase in the cost range or GMP is ultimately related to cost uncertainty, indicating that the contractor's estimation ability is an important factor in assessing the risk level of a GMP contract. The preconstruction phase of CMR is vital for enhancing the accuracy of cost estimation. Thus, the contractor's estimation can be improved by implementing CMR. However, as the existing DBB method is currently widely used in Korea, stakeholders are not accustomed to participating in a collaborative process and thus may have considerable difficulty in communicating with other participants. Therefore, domestic contractors should seek to enhance their competency in preconstruction services by forming a partnership or joint venture with overseas consulting companies that have already implemented a systematic collaboration process.

Utilizing a GMP contract within a CMR application could highlight the importance of risk management in Korea. In the past, many Korean companies have tended to depend on sales strategies rather than business management strategies. However, the capability of a company can be directly related to the possibility of winning a GMP contract. In particular, estimation accuracy, which varies according to the capabilities of each company, is essential when setting the GMP. In this regard, a GMP contract will have positive effects on the development of the Korean construction industry.

In this paper, the proposed model is based on uncertainty of actual cost. Therefore, rather than validating the accuracy of the model by using the actual cost, this paper focused on presenting the reference that confirmed the risk transfer level based on the change of *K*-ratios. As can be confirmed from the analysis results, it is necessary to minimize the cost volatility for a successful GMP contract. Accordingly, it is very important to analyze the factors that influence cost volatility. In future work, the various factors that have an impact on the GMP must be studied to maximize the positive effects of the framework proposed in this paper. A comparative analysis of the effect of each factor on the change in the GMP will help Korean construction companies who are attempting to introduce GMP contracts to perform their preconstruction services effectively.

Data Availability

Data generated or analyzed during the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Identifying Critical Bankability Criteria for PPP Projects: The Case of China

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Public-private partnership (PPP) projects employ a high leverage in terms of debt finance needed by the private consortium. Debt finance providers need to know the bankability-related issues of PPP projects to make the timely arrangement of debt financing and avoid funding problems. However, there is still a lack of a systematic research on the bankability of PPP projects despite the worsening debt arrangement situation for PPP projects after the credit crisis and economic recession from 2008. To bridge this knowledge gap and enhance the practical debt arrangement of PPP projects, this study aims to identify and prioritize the critical bankability criteria of PPP projects. To achieve the objectives, 41 bankability-related criteria were first identified from a comprehensive literature. A structured questionnaire survey was then conducted with 31 industry experts in China who worked in financial institutes and had experienced PPP projects to investigate the relative importance of each criterion. To handle the uncertainty and vagueness of the subjective evaluation from surveys, this study analyzed the relative importance weight of each criterion using a proposed fuzzy analytical hierarchy process-based approach. The results showed that political environment, economic environment, shareholders' credibility, financial market, legal system, public sector's reliability, financial structure, and regulatory framework were ranked as the top eight critical bankability criteria. The findings of this study first contributed to the project finance body of knowledge for the bankability of PPP projects. Moreover, the outputs of this study would provide valuable information to the private and public sectors for formulating strategies on improving the bankability of PPP projects.

1. Introduction

As an efficient procurement method of the public infrastructure projects or services, the public-private partnership (PPP) approach has been widely adopted in many countries [1]. For instance, China has initiated 13,554 PPP projects costing 2,612 billion dollars until the end of June 2017 [2–4]. Through the PPP approach, the public sector can alleviate the shortage of the infrastructure investment and increase the efficiency of infrastructure provision [5]. As for the private sector, they can broaden their investment channel without severely endangering their corporate assets because of the off-balance sheet finance arrangement [6]. The main or sole source to meet financial obligations is the cash flows of a PPP project. In addition, the banks have no recourse or limited recourse to the private sector's corporate assets [6, 7].

Projects developed using PPP approach (PPP projects) are well known for the high leverage ranging from 50% to 90%, relying extensively on the debt capital provided by the debt holders such as banks and other financial institutions [8]. Therefore, raising sufficient funds via the debt channel is a key task for PPP sponsors and project companies [9]. However, international capital markets have experienced high levels of instability and adversely affected the funding arrangements for social and economic infrastructure projects since 2008, leading to limited availability of equity and debt capital and a higher cost of capital [10, 11]. Moreover, the market access has been difficult for both the public sector and the private sector, leading to banks becoming the main source of funds for PPP projects [10, 12]. Furthermore, banks were unwilling to commit to lending terms for anything other than a short period in some countries [12].

Because of the adverse situation of the financial market, several projects failed to be procured through the PPP approach because of unsuccessful debt arrangements [13–15]. Moreover, many researchers identified that the debt arrangements of PPP projects greatly hindered the eventual progress to the construction stage. Thomas [16] identified that delays in debt arrangements constitute a critical risk in the development phase of BOT projects in India. Cheng et al. [17] indicated that prolonged negotiations between borrowers and financiers abort the commencement of PPP projects. Moreover, Merna and Khu [18] pointed out that PPP promoters were sometimes unable to raise funds even if they had obtained the franchise from the government because of their lack of project financing techniques and the understanding of associated risks. In addition, funding is a major problem for PFI projects especially launched by small- or medium-sized companies [17]. The difficulty in raising the finance, the high cost of financing, and even being unable to close financing within the time frame stipulated in the concession agreement all could lead to the failure of financial close [7, 19].

Considering the significance of the debt for PPP projects and the difficulties in securing loans for a successful financial close, it is an important requisite for project stakeholders, especially project sponsors and the relevant public sector, to consider the bankability-related issues from the outset of a PPP project. A PPP project is considered bankable if lenders are willing to finance it [20]. Moreover, establishing enhanced bankability for a PPP project is because ultimately the financial market will judge the project on its own merits without the traditional government repayment guarantees [19]. Readily bankable PPP projects are prioritized over more-needed infrastructure projects by banks [10]. Bankable, generating enough cash flow, and reflecting project and financing term were identified as the top three most important expectations from stakeholders of PPP projects [7]. Furthermore, the lessons from the subprime mortgage led to banks enhancing their own internal credit rating systems instead of completely relying on the credit risk assessment of external credit rating agencies. Therefore, the research on the bankability assessment of PPP projects is important for paving the way towards the successful and sustainable development of PPP projects [21].

Up until now, the research on the bankability assessment of PPP projects is still lacking. Considering that the bankability implies a set of criteria that investors consider in approving project finance, this study aimed to identify and prioritize the critical bankability evaluation criteria (hereafter referred to as bankability criteria) for PPP projects from the bank's perspective. The findings of this study can enrich the project finance body of knowledge in the bankability assessment of PPP projects. Moreover, outcomes of this study can help PPP project stakeholders, especially the public and private sectors, make rational decisions to form bankable PPP projects, paving the way to the successful and sustainable development of PPP projects.

2. Background

2.1. Rational of Bankability Evaluation. Up until now, there is no uniform definition of the bankability of a project. Commonly, a PPP project is bankable if lenders are willing to finance it or the sponsor can convince the lenders to support it [9, 20]. From the assessment perspective, a bankable project involves a solid financial, economic, and technical plan, with a risk allocation scheme appropriate for the nature of the project, the risks involved, and the interests of the lenders, implying an acceptable credit risk [8, 22]. Moreover, the bankability of PPP projects consists of the key common bankability dimensions in general and a common set of bankability criteria against which the key dimensions are evaluated [8, 23]. Considering the quantitative loan analysis, the lenders believe that a project is bankable if the project company has the ability to service the principal and interest payment. In addition, the exposure of the lenders to default by the borrowers is acceptable [9, 22].

The lessons from the subprime mortgage led to banks not completely relying on the credit risk assessment of external credit rating agencies [24]. Each bank has or starts to enhance its internal credit rating system to evaluate the credit of a PPP project [22]. Generally, the banks' internal credit rating systems are not revealed to outsiders as they are carried out by the banks' personnel. Only the banks' staffs who work with these bankability evaluation models, such as the bank directors and debt evaluators, know the rating system. Moreover, there is no common internal credit rating system for all banks. Comparing with statistical models developed by external credit rating agencies, the banks generally believe that a properly managed judgmental rating system delivers more accurate estimates of risk [24].

2.2. Identified Bankability Criteria. To identify the critical bankability criteria, this study adopted the analytic hierarchy process (AHP) approach. As a well-known structured technique for dealing with the complex decision, the decision problem is first decomposed into a hierarchy of more easily and independently analyzed subproblems. Experts' opinions and evaluation scores are then integrated into the simple elementary hierarchy system [25]. AHP approach has been widely used to deal with PPP-related issues [26, 27].

Through a comprehensive literature review and case studies, this study identified 41 bankability criteria that determine the bankability of a project or are of primary importance to the lenders in assessing a loan application. This study further classified them into six dimensions: (1) economic and political environment; (2) legal and regulatory environment; (3) project specificity; (4) project financial structure; (5) third party risk allocation; and (6) contract arrangement. The bankability dimensions and criteria under each dimension are summarized in Table 1.

2.2.1. Economic and Political Environment. Laishram and Kalidindi [29] identified that social-economic characteristics and economic strength were two extremely important criteria in assessing the desirability of a PPP project from a debt

Table 1: Identified bankability criteria for PPP projects.

S/N	Bankability criterion	References									
		1	2	3	4	5	6	7	8	9	10
D1	Economic and political environment										
D1.1	Economic environment		√	√							√
D1.2	Competition condition				√						√
D1.3	Financial market									√	
D1.4	Political environment			√							
D1.5	Public opinion						√				
D1.6	Tax policies			√							
D1.7	Currency issues			√					√		
D2	Legal and regulatory environment										
D2.1	Legal system			√	√			√			
D2.2	Regulatory framework			√							
D2.3	Enforceability			√	√						
D2.4	Nationalization and expropriation			√				√			
D2.5	Procurement process								√		
D2.6	Intervention right			√							
D3	Project specificity										
D3.1	Project definition		√	√			√				
D3.2	Feasibility studies		√	√							
D3.3	Capacity of the technology			√	√						
D3.4	Site acquisition and access			√							
D3.5	License, permits, and authorizations		√	√				√			
D3.6	Infrastructure issues			√							
D3.7	Environmental standards		√	√			√				
D3.8	Labor force			√							
D3.9	Size of the project		√	√			√				
D4	Project financial structure										
D4.1	Shareholders' credibility	√		√	√	√			√		√
D4.2	Public sector's reliability				√			√			
D4.3	EPC contractor's credibility				√						
D4.4	Financial structure		√	√		√			√		√
D4.5	Financial flexibility		√	√		√					√
D5	Third party risk allocation										
D5.1	Insurance arrangement			√		√				√	√
D5.2	Environmental and other legal/regulatory issues			√							
D6	Contract arrangement										
D6.1	Concession agreement			√		√					√
D6.2	Concession period			√		√					
D6.3	Support agreement/guarantee					√			√		√
D6.4	Termination provisions			√							
D6.5	Construction contract		√	√							√
D6.6	Operation and maintenance agreement		√	√							√
D6.7	Offtake purchase agreement			√							√
D6.8	Input supplier agreement			√							√
D6.9	Guarantee from multilateral investment agency				√			√		√	
D6.10	Direct agreement				√						
D6.11	Catastrophic risk			√				√			
D6.12	Arbitration						√				

References: (1) Lopes and Teixeira Caetano [28]; (2) Laishram and Kalidindi [29]; (3) Delmon [8]; (4) Gatti [30]; (5) Zhang [23]; (6) Davis [31]; (7) Wang et al: [32]; (8) Wang et al: [19]; (9) Regan et al: [11]; (10) Zhang [33].

financing perspective. Moreover, considering the practical requirements of the lenders when reviewing a project, Delmon [8] found that the economic and political viability and currency issues were important bankability issues. Furthermore, the tax regime applicable to PPP projects must be sufficiently stable because the lenders need to forecast the exposure to tax liability and plug into the financial model [8]. In addition, Gatti [30] and Zhang [33] emphasized the importance of the competition condition in the economic environment to the bankability of a PPP project. Through many real case studies, Davis [31] revealed the importance of public opinion to the success of PPP projects.

2.2.2. Legal and Regulatory Environment. Contract enforceability depends on a series of factors such as a country's judicial tradition as well as the degree of economic development in a country. Gatti [30] indicated that lenders felt less protection in nations where civil law is in force than in nations where the common law is in force. Moreover, Delmon [8] explained that lenders would want to consider the legal system applicable to a project in view of a long-term commercial agreement. The availability of justice, enforceability, and nationalization and expropriation were important criteria from the lenders' perspective. Change in law and expropriation were identified two of the six most critical risks affecting the finance of China's BOT projects [32]. In addition, among the procurement procedure, seeking a realistic target date for financial close is highly critical [19].

2.2.3. Project Specificity. After assessing the desirability of a PPP road project from a debt financing perspective, Laishram and Kalidindi [29] found that (1) the feasibility study was one of the extremely important criteria to a debt financing and (2) the permits and site clearances were two of the fairly important criteria to a debt financing. Practically, lenders prefer to ensure that protections are provided to the project company to avoid any cost increase and time delay because of the changes in the required permits and licenses [8, 32]. Moreover, in terms of the practical requirements of the lenders when reviewing a project, Delmon [8] explained that lenders usually attach great importance to the capacity of the technology to be used and its appropriateness for the site and the region. International financing organizations conventionally prefer to have a separate review of the capacity of the technology performed by an independent expert [8, 30]. Furthermore, the sufficient local infrastructures, including transportation systems, roadways, electricity, water, and other utilities, and local services were greatly important to the bankability of a PPP project [8].

2.2.4. Project Financial Structure. Lenders believe that the special purpose vehicle (SPV) shareholders which have the high creditworthiness and reliability would make a strong commitment to a project [8, 30]. Based on an empirical study to identify the determining characteristics of a firm to be engaged in a PPP project, Lopes and Teixeira Caetano [28] disclosed that larger and more leveraged firms had a higher probability of being engaged in a PPP project. The strong financial capability, sufficient commercial experience, and technical expertise of the concessionaire were an important prerequisite to the successful development of a PPP project [8, 23]. Compared with the private sector, the public sector's reliability and creditworthiness are often viewed as the critical risk for PPP projects [30, 32]. Factors, such as corruption and rent-seeking behavior, often turn a decision of a PPP project against lenders [30]. As one of the main shareholders, the EPC contractor's credibility, which is often examined through a due diligence investigation, directly determines the completion risk of a PPP project and affects the lenders' interest [30].

Moreover, the results of Laishram and Kalidindi [29]'s empirical study showed that some elements of a financial structure, such as debt service cover ratio, debt-equity ratio, and debt service reserve, and the financial flexibility of a PPP project was extremely important to a debt financing. Essentially, the health of the project structure, the commercial plan, and the forecast revenue stream convince the lenders to provide financing to a PPP project [8]. Furthermore, the findings from a survey on 35 identified financial criteria showed that the price and adjustment mechanism, the attractiveness of main loan agreement, sound financial analysis, and minimal financial risks to the clients were the top four most significant financial criteria [23, 33].

2.2.5. Third Party Risk Allocation. The sufficient insurance coverage of a PPP project would further protect the lenders from risks and is viewed as the critical financial criteria measuring the financial capability of a PPP project [11, 23, 33]. A PPP project must have in place a comprehensive insurance scheme, avoiding gaps or overlapping coverage [8]. Moreover, lenders would prefer that the project company is isolated from sanctions for the breach of environmental regulations and compensation for environmental damage [8].

2.2.6. Contract Agreement. To ascertain that all risks are appropriately allocated to various players, lenders would closely look at the network of contracts with the SPV [30]. The relevant contracts include the concession agreement, EPC contract or construction contract, operation and maintenance (O&M) agreement, offtake purchase agreement, input supply agreement, termination provisions, and direct agreement [8, 29, 30, 33]. Moreover, the government's guarantees/support/comfort letters would enhance the bankability of a PPP project and, to some extent, reduce the relevant political risks [19, 33]. Furthermore, in terms of international financing, obtaining the guarantee from multilateral investment agency is regarded as the most effective measure in mitigating expropriation risk and obtaining the support of the project developer's home government [32]. In addition, the force majeure and relevant arbitration when a dispute occurs were also identified as critical risks in PPP development [31, 32].

3. Methodology and Data Presentation

3.1. Data Collection and Presentation. As a systematic method of collecting data, the questionnaire survey technique has been widely used to collect professional views [7, 34, 35]. This study conducted a questionnaire survey to investigate the relative importance weights of the bankability criteria. To develop the questionnaire, a comprehensive literature review of the bankability criteria was first carried out. Afterward, a two-step process was adopted to test the validity and relevance of the questionnaire. The questionnaire was first reviewed by an expert on question construction, ensuring that the survey did not contain common errors such as leading, confusing, or double-barreled questions. Then, a presurvey was conducted with three PPP industry professionals from the bank, who had several years' experience in PPP projects. Their feedback was taken into consideration to finalize the questionnaire.

The finalized questionnaire first included the questions meant to profile the respondents. Furthermore, the 41 bankability criteria were presented in the questionnaire. Moreover, the brief description of each bankability criterion was provided to ensure consistency throughout the survey. Subsequently, the respondents were asked to conduct the pair-wise comparison of the importance of these bankability criteria using the five linguistic terms: equal importance, weak importance, moderate importance, strong importance, and extreme importance. The questionnaire was designed in a bottom-up manner. The questions relating to the criteria under different dimensions were presented in front, while those relating to dimensions were presented at behind. This bottom-up approach can enhance the respondents' understanding of the criteria and their contribution to each corresponding dimension. In addition, postsurvey interviews were conducted with three industry experts who possess the relevant experience in PPP financing. Their views helped us to validate the findings of the survey questionnaire and to provide a better understanding of the findings.

The population of this study consisted of all PPP professionals who had PPP financial experience in China, especially experts from banks. A total of 130 sets of survey questionnaires were randomly sent out through email to gather responses from the banks or financial institutions. Finally, 31 complete sets were received, representing a response rate of 23.8%. Although the sample size was not large, statistically analysis could still be performed because the central limit theorem holds true even when the sample size is no less than 30 according to the generally accepted rule [36, 37].

Among the 31 respondents, 30 respondents were from the banks and one respondent from a trust company that acted as a debt finance provider. Moreover, the respondents from the banks were from eight different commercial banks that provided a large portion of the loan for PPP projects in China such as China Construction Bank and Bank of Communications. Considering the business confidentiality, this study did not disclose the names of the involved banks. In addition, the respondents from the banks were holding the positions of bank director, loan evaluator, and marketing manager. The relatively small sample size was mainly caused by two reasons. First, only those with good PPP finance-related experiences and were willing to perform the survey would be approached to send the survey form. This has significantly reduced the pool size of the potential respondents. Second, some of the experienced practitioners contacted were reluctant to share their opinions because of business confidentiality. Although the size of the sample was relatively small, the knowledge and judgments of the respondents were reasonable considering the experience of the respondents. Considering the area of the respondents, this study was a location-based study.

3.2. Fuzzy AHP for Ranking of Bankability Criteria. This study adopted the fuzzy set theory to handle the uncertainty and vagueness of the subjective evaluation of the importance of the identified bankability criteria. Zadeh [38] developed the fuzzy set theory to handle such kind of impreciseness of human subjective judgment. Buckley [39] later extended the hierarchical analysis to the case where experts were allowed to use fuzzy ratios in place of exact ratios. Fuzzy analytic hierarchy process (Fuzzy AHP) methodology has been used in research on various issues of PPP projects [26, 40].

Instead of using a precise number to assess the priority of a criterion, a triangle fuzzy number $\widetilde{r} = (a, m, b)$ was used to express fuzzy ratios. The geometric mean technique was adopted to determine the fuzzy weights of criteria [39].

3.2.1. Comparing the Dimensions and Criteria via Linguistic Terms. As stated above, the pairwise comparisons of both the dimensions and criteria were performed using a set of linguistic terms which were adapted from Saaty [41] and Saaty [42], namely, "equal importance," "weak importance," "moderate importance," "strong importance," and "extreme importance." The triangular fuzzy number was employed in this study first because it expresses most closely the meaning of "about x," which is a common fuzzy thinking pattern of human beings [26]. Second, the triangular fuzzy number can be utilized in the situations when the comparisons in pair and judgments are uncertain or fuzzy [43].

The linguistic terms were then transformed into triangular fuzzy numbers in order to facilitate subsequent fuzzy arithmetic operations. The linguistic values and triangular membership functions are shown in Table 2 with the middle value denoting the most likely or typical value and the lower and upper bounds denoting the lower and upper membership values, respectively. In addition, the spread reflects the fuzziness of the term.

If a fuzzy number $\widetilde{r} = (a, m, b)$ represents the importance of comparison of criterion C1 to criterion C2, then $\widetilde{r}^{-1} = ((1/b), (1/m), (1/a))$ represents the inverse comparison of criterion C2 to criterion C1. The pair-wise criteria comparison matrix $\widetilde{A}_j^k$ was given by the following equation, where $\widetilde{r}_{jil}^k$ denotes the k^{th} expert's preference of criterion i over criterion l under dimension j, via fuzzy triangular numbers:

$$\widetilde{A}_j^k = \begin{bmatrix} \widetilde{r}_{j11}^k & \widetilde{r}_{j12}^k & \cdots & \widetilde{r}_{j1l}^k \\ \widetilde{r}_{j21}^k & \widetilde{r}_{j22}^k & \cdots & \widetilde{r}_{j2l}^k \\ \cdots & \cdots & \cdots & \cdots \\ \widetilde{r}_{ji1}^k & \widetilde{r}_{ji2}^k & \cdots & \widetilde{r}_{jil}^k \end{bmatrix}. \quad (1)$$

The evaluation of the importance of the criteria was based on the survey results. Each expert gave his/her judgment of the importance of the criteria using linguistic terms.

3.2.2. Computing Average Preference. The average fuzzy preference was given by the geometric mean of the preferences of all experts as shown in Equation (2). The revised pairwise comparison matrix was depicted in Equation (3). In

Table 2: The linguistic terms and the corresponding triangular fuzzy numbers.

Scale of importance	Linguistic term	Triangular fuzzy numbers
1	Equal importance (EqI)	(1, 1, 1)
3	Weak importance (WI)	(1, 3, 5)
5	Moderate importance (MI)	(3, 5, 7)
7	Strong importance (SI)	(5, 7, 9)
9	Extreme importance (ExI)	(7, 9, 9)

the following equations, r_{jil} denotes the average preference of criterion i over criterion l under dimension j:

$$r_{jil} = \left[\prod_{k=1}^{K}\left(\tilde{r}_{jil}^{k}\right)\right]^{1/K}, \tag{2}$$

$$\tilde{A}_j^k = \begin{bmatrix} \tilde{r}_{j11}^k & \tilde{r}_{j12}^k & \cdots & \tilde{r}_{j1l}^k \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{r}_{ji1}^k & \tilde{r}_{ji2}^k & \cdots & \tilde{r}_{jil}^k \end{bmatrix}. \tag{3}$$

3.2.3. Computing Weight of the Fuzzy Matrices. The following basic fuzzy operations shown from Equations (4)–(7) are required for computing the importance weights of the criteria. Given fuzzy number $\tilde{X} = (a_1, m_1, b_1)$ and $\tilde{Y} = (a_2, m_2, b_2)$, then

$$\tilde{X} \oplus \tilde{Y} = (a_1 + a_2, m_1 + m_2, b_1 + b_2), \tag{4}$$

$$\tilde{X} \oplus \tilde{Y} = (a_1 \cdot a_2, m_1 \cdot m_2, b_1 \cdot b_2), \tag{5}$$

$$\tilde{Y}^{-1} = \left(\frac{1}{b_2}, \frac{1}{m_2}, \frac{1}{a_2}\right), \tag{6}$$

$$\frac{\tilde{X}}{\tilde{Y}} = \left(\frac{a_1}{b_2}, \frac{m_1}{m_2}, \frac{b_1}{a_2}\right). \tag{7}$$

The weightings of criterion $\tilde{W}_{ji}$ are geometric mean as follows:

$$\begin{aligned} \tilde{W}_{ji} &= \left(\prod_{l=1}^{n} r_{jil}\right)^{1/n} \otimes \left[\sum_{i=1}^{n}\left(\prod_{l=1}^{n} r_{jil}\right)^{1/n}\right]^{-1}, \\ & i, l = 1, 2, 3, \ldots, n; \quad j = 1, \ldots, 6, \\ &= \left(a_{ji}, m_{ji}, b_{ji}\right). \end{aligned} \tag{8}$$

3.2.4. Defuzzification of the Fuzzy Weights. Since the triangular fuzzy number was adopted in this research, the level rank method using the concept of α-cut was employed to defuzzify the fuzzy weights $\tilde{W}_{ji}$ [44]. An α-cut of a fuzzy set embraces all elements of the fuzzy set whose degrees of membership to this fuzzy set are at least equal to α [45]. The membership scale of the fuzzy variable $\tilde{W}_{ji}$ is cut with the aid of r randomly chosen α levels. For example, the defuzzification value M_{ji}^t of the fuzzy variable $\tilde{W}_{ji}$ at the t^{th} α-cut level is determined as the arithmetic mean of the lower and upper bounds of the membership interval at the t^{th} α-cut level. This concept was presented by Equation (9) and depicted in Figure 1. The advantage of this method is that the shape of the membership function is considered:

$$M_{ji} = \frac{1}{r} \cdot \sum_{t=1}^{r} M_{ji}^t = \frac{1}{r} \cdot \sum_{t=1}^{r} \frac{a_{ji}^t + b_{ji}^t}{2}. \tag{9}$$

3.2.5. Normalization. Finally, to conform with traditional AHP, the importance weights of the criteria and the dimensions were normalized by ensuring that they sum to 1, as given by the following equation:

$$w_{ji} = \frac{M_{ji}}{\sum_{i=1}^{n} M_{ji}}. \tag{10}$$

The importance weights of bankability dimensions were similarly derived using Equations (1)–(10). Using w_j to represent the normalized importance weight of dimension j, the overall importance weight of criterion i is the product of the importance weight of criterion i under dimension j and the importance weight of dimension j, as computed by Equation (11). The calculation of overall importance weight ensures that each bankability criterion is ranked at the same level. Because the fuzzy AHP calculation is very complex, this study developed a program written in Microsoft C# to process the survey data:

$$w_i = w_j \cdot w_{ji}. \tag{11}$$

4. Results and Discussion

4.1. Consistency of Evaluation Results. Before analyzing the pertinent finding of this study, this study carried out the Pearson chi-square test (χ^2) to reveal the evaluation consistency of the samples within each set [36]. The hypothesis of this test was that each respondent's evaluation was the same or consistent with the geometric mean evaluation. The calculated χ^2 value for the sample sets of the bank was 45.70. Because the relevant critical value for χ^2 at 95% confident level is 55.76, the hypothesis cannot be rejected. Therefore, it is legitimate to use the geometric mean of the evaluations from the respondents to reflect the relative importance weights of the bankability criteria.

4.2. Importance Weights of Bankability Dimensions. Because the banks' perception is crucial to the establishment of a loan, this study first analyzed the importance weights of the bankability dimensions from the banks' perspective

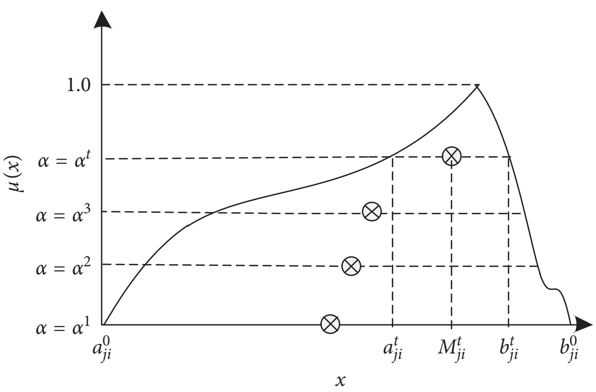

Figure 1: The level rank method of defuzzification.

using the fuzzy AHP-based method explained above. The relative importance weights of the bankability dimensions from the banks' perspective are presented in Table 3. The results showed that project specificity (D3), project financial structure (D4), and economic and political environment (D1) were ranked as the top three important dimensions from the banks' point of view, making up 64.81% of the total weight.

Because the revenue cash flows of a PPP project are the main or sole source to meet the financial obligation, the banks must first ensure that the project is financially well structured and profitable [6]. The bankable consideration was of great importance to the stakeholders of PPP projects [7]. Moreover, the project specificity and project financial structure represent the competitiveness of a PPP project in the market, indicating that the above results were reasonable/believable [3, 33]. Furthermore, PPP projects are usually mega projects or infrastructure projects with a vast amount of capital investment. The economic and political environment will easily affect the investment decision of a PPP project from the banks' point of view [31]. In addition, the findings revealed that the banks do have an emphasis on some of the bankability dimensions.

4.3. Importance Weights of Bankability Criteria. Using the above-explained fuzzy AHP method, this study analyzed the relative importance weights of the bankability criteria in China from the banks' perspective. For the sake of succinct presentation, this study listed the top twenty criteria whose importance weights were above the average, as shown in Table 4. Moreover, the importance weights of the top twenty criteria made up 71.33% of the total weight, indicating that the top twenty criteria generally covering the major bankability concerns from the bank's perspective.

Among the identified 41 criteria, the top ten criteria, which were within the first quartile of all criteria, that affect the bankability of a PPP project were political environment (D1.4), economic environment (D1.1), shareholders' credibility (D4.1), financial market (D1.3), legal system (D2.1), public sector's reliability (D4.2), financial structure (D4.4), regulatory framework (D2.2), EPC contractor's credibility (D4.3), and financial flexibility (D4.5). This study briefly discussed these criteria as follows.

Political environment (D1.4) (importance weight = 6.94%), legal system (D2.1) (importance weight = 4.95%), and regulatory framework (D2.2) (importance weight = 3.74%) were ranked first, fifth, and eighth, respectively. It is well known that PPP projects are mostly infrastructure projects or public-related projects, involving a vast amount of investment. From the bank's perspective, the desirability of a PPP project is easily affected by the macroenvironment of a country [29, 46]. Moreover, the success of PPP projects would be greatly affected by the cooperation relationship between the public and private sectors. Once there is any divergence between the two parties, the legal system determines the contract enforceability and is the baseline for setting the dispute [8]. Any change in law would be critical risks for PPP projects, especially in countries using the civil law [32].

Economic environment (D1.1) (importance weight = 6.49%) and financial market (D4.1) (importance weight = 5.42%) received the second position and fourth position, respectively. In a sound and stable economic environment, the willingness of the consumer to pay for the use of infrastructure is high, ensuring the cash flow of a proposed project [8]. Furthermore, the condition of the financial market greatly affects the availability of the lending for PPP projects. The difficulties in the debt arrangements for PPP projects after the credit crisis and economic recession well prove this [12, 47]. In a nutshell, the ecosystem that consists of the political environment and economic environment should be sound enough [48].

Shareholders' credibility (D4.1) was ranked third (importance weight = 5.60%). The shareholder is the party who commit to developing and operating a PPP project in a long concession period. The experts in the postinterviews pointed out that the strong financial capability of the shareholders was an important prerequisite for a successful debt approval. The bank usually assumes that a PPP project developed by shareholders with a high credibility is more bankable even if the bank has limited recourse or nonrecourse to the shareholders' assets outside the project [23]. The bank wants to ensure that the shareholders have sufficient commercial experience, financial standing, technical capability, and operation ability to implement the project, thereby protecting the lenders' interests [3, 8, 23, 49]. This may be the reason that larger and more leveraged firms had a higher probability of being engaged in a PPP service concession agreement and receiving the loan from the banks [28]. Moreover, the operation ability of the shareholder draws great attention recently because many projects step into the operation stage. The operation stage is usually less capital intensive but determines the fulfillment of the revenue of a PPP project [3, 49]. Furthermore, the credible shareholder implies credible equity financing which is critical to the success of a PPP project and often influences the ability of a company to secure the further debt financing from the banks' perspective [8, 19].

Public sector's reliability (D4.2) was ranked sixth (importance weight = 4.59%). Even if there is a concession

Table 3: Relative importance weights of bankability dimensions from the banks' perspective.

Bankability dimension	Importance weight of bankability dimension (%)
Economic and political environment (D1)	17.34
Legal and regulatory environment (D2)	12.68
Project specificity (D3)	25.08
Project financial structure (D4)	22.39
Third party risk allocation (D5)	9.82
Contract arrangement (D6)	12.68

Table 4: Relative importance weights of the twenty criteria from the banks' perspective.

Bankability criterion	Ranking	Importance weight (%)	Subtotal (%)
Political environment (D1.4)	1	6.94	
Economic environment (D1.1)	2	6.49	18.85
Financial market (D1.3)	4	5.42	
Legal system (D2.1)	5	4.95	
Regulatory framework (D2.2)	8	3.74	
Enforceability (D2.3)	11	2.92	16.84
Intervention right (D2.6)	13	2.63	
Nationalization and expropriation (D2.4)	14	2.60	
License, permits, and authorizations (D3.5)	18	2.36	
Shareholders' credibility (D4.1)	3	5.60	
Public sector's reliability (D4.2)	6	4.59	
Financial structure (D4.4)	7	3.77	20.82
EPC contractor's credibility (D4.3)	9	3.52	
Financial flexibility (D4.5)	10	3.34	
Insurance arrangement (D5.1)	12	2.81	5.40
Environmental and legal issues (D5.2)	15	2.59	
Concession agreement (D6.1)	16	2.56	
Support agreement/guarantee (D6.3)	17	2.46	9.42
Termination provisions (D6.4)	19	2.25	
Concession period (D6.2)	20	2.15	
		Total weight	71.33

agreement between the public and private sectors, the public sector who has a low reliability has a high probability to break the contract relationship when difficulties attend during the project development [32]. Moreover, the offtakers, most of whom have a public or government background, will easily default if the public sector's reliability is low. This is clearly reflected in many real projects such as Changchun Huijin waste water BOT project in China, Dabhol power project in India, and Samalayuca II in Mexico [1, 31].

Financial structure (D4.4) (importance weight = 3.77%) and financial flexibility (D4.5) (importance weight = 3.34%) were ranked seventh and tenth, respectively. For a PPP project, the main or sole source to meet financial obligations is the project cash flow [6, 47]. An optimal and operational financial structure that reflects the characteristics of project financing is extremely important for both the private sector and the bank because it synchronizes both profitability and repayment capacity [50, 51]. From the bank's perspective, only truly good projects with real, tangible service provision, and well structured should be considered to be implemented as PPP projects and be financed [48]. Financial terms calculated based on the financial structure, such as the debt service coverage ratio, sensitivity, debt service reserve and debt-equity ratio, were extremely important to a debt financing, greatly influencing the desirability of a PPP project from a debt financing perspective [29]. Moreover, reasonable and flexible financial arrangements are also needed to deal with unforeseen risks or problems [47]. For instance, many transportation PPP projects exposed to the financial risk of low profitability due to the inaccurate forecast of traffic volume [52, 53]. In this condition, flexible financial arrangements should be considered to overcome the uncertainties.

EPC contractor's credibility (D4.3) (importance weight = 3.52%) was ranked ninth. The related experience, financial strength, and technical capability of the EPC contractor ensure the completion of a PPP project on time and within budget, partially securing the banks' interest in PPP projects. Moreover, many engineering contractors participate in PPP projects and become a major constituent of the private sector in PPP projects [3, 54]. Engineering contractors with a high credibility bring the added value to PPP projects because they have a strong construction and financing capabilities and can improve the development efficiency [3]. Through the due diligence reporting, a closer examination of the contractor's construction and financing capability could reduce EPC contractor-related risks [30].

5. Conclusion and Recommendations

For PPP projects, raising sufficient funds via the debt channel is a key task for all project stakeholders. Considering the lack of a systematic research on the bankability of PPP projects, this study proposed the fuzzy AHP-based approach to identify the critical bankability criteria of PPP projects from a debt financing perspective. A total of 41 bankability-related criteria were first identified from a comprehensive literature review and further classified into six dimensions. Afterward, a structured questionnaire survey was conducted with 31 industry experts from the bank in China to investigate the relative importance of each criterion. Finally, this study analyzed the relative importance weight of each criterion using the proposed fuzzy AHP-based approach that can handle the uncertainty and vagueness of the subjective evaluation from surveys. The results of this study first showed that project specificity, project financial structure, and economic and political environment were ranked as the top three important dimensions from the bank's point of view. Moreover, the top twenty criteria, the importance weights of which made up 71.33% of the total weight, represented the major bankability concerns from the bank's perspective. Furthermore, political environment, economic environment, shareholders' credibility, financial market, legal system, public sector's reliability, financial structure, regulatory framework, EPC contractor's credibility, and financial flexibility were identified as the top ten most critical bankability criteria of PPP projects. In addition, the importance weights of the top twenty criteria made up 71.33% of the total weight, representing the major bankability concerns from the bank's perspective.

With the aim of identifying the critical bankability criteria for successful PPP project finance, the empirical results of this study fill a gap in the project finance body of knowledge for the bankability of PPP projects. Moreover, the findings of this study would provide valuable information to the private and public sectors for formulating strategies on improving the bankability of PPP projects. Furthermore, the research methodology proposed in this study could be extended and customized to suit for different stakeholders of PPP projects and different countries implementing PPP projects.

Although the objectives have been achieved, this study still suffers from several limitations. First, the importance weights proposed in this study may be biased by the respondents' judgments and experience because they were subjective. Besides, the findings from this study were well interpreted in the context of China, which may be different from the context of other countries. Nonetheless, this study still provides an operational method to identify the bankability criteria for PPP projects which can be modified and customized to suit for the context of other countries. Moreover, this study provides an in-depth understanding of the critical bankability criteria because it is widely acknowledged that China government has been promoting PPP to facilitate the infrastructure development.

Future studies would use the developed fuzzy AHP-based method to investigate whether the private and public sectors have the same perception on the importance weights of bankability criteria with the bank. If different parties have different perceptions on bankability criteria, there will be information asymmetry, hindering the financial close of PPP projects. Moreover, future studies would identify best practices to improve the bankability of PPP projects and increase the efficiency and success rate of financial arrangement for PPP projects.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

Table A1: qualitative bankability criteria and remarks, which briefly describe each bankability criterion to ensure consistency throughout the study. (*Supplementary Materials*)

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Research Article

Sustainable Infrastructure Design Framework through Integration of Rating Systems and Building Information Modeling

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BIM (building information modeling) can be the basis for carrying out various performance analyses. Sustainable infrastructure rating systems are suitable tools for assessing an infrastructure's environmental performance. It is necessary to integrate them in the design process. The research adopted a thorough literature review to follow the development trends, interviews with professionals from the academia and industry, and a critical analysis of technical requirements for integrating BIM tools and infrastructure sustainability rating systems in the design process. This study propagates a conceptual framework for integrating sustainability rating systems by introducing BIM with a sustainability metric plug-in. The adoption of the proposed solution allows for what-if scenarios to better support the incorporation of sustainability into design decisions and the assessment of sustainability at the design phase of the infrastructure project. The framework is used to refine designs and ensure that sustainable goals are met and to demonstrate compliance with regulatory requirements. This paper concludes that greater emphasis should be placed on supporting technical requirements to facilitate the integration of BIM and sustainability rating systems. It defines the possibility of BIM adoption to influence the sustainable project performance in the infrastructure. This framework could streamline the sustainable design process and lead to more integrated infrastructure delivery.

1. Introduction

Infrastructure sustainability has attracted great attention [1]. It is rife with propaganda but requires much greater practical solutions. As the largest sustainability opportunities lie in the planning phase, sustainable design can be a critical success factor. All of these goals lead to more sustainable solutions for the infrastructure and are possible to be achieved with BIM.

Building information modeling (BIM) has been used in buildings for many years [2] and now it is applied across the entire built environment [3]. Sustainable designs adopt BIM as a basis for carrying out the various performance analyses [4]. BIM can potentially support the early design sustainability analysis. The major problem appears to be that it is not defined what infrastructure performance knowledge should be in the BIM. In theory, BIM is well suited to sustainability due to the capacity of BIM to inventory beneficial data for measuring life cycle costs or performing energy analysis. But in practice, a lot of problems have been arising related to interoperability, regulation, and compliance issues.

The objective of this research is to propose a sustainable design approach for infrastructure, focusing on sustainability rating systems as decision-making criteria along with BIM data. This paper analyzes the possibility of integrating rating systems and BIM in sustainable infrastructure design from literature and industry and then presents a theoretical framework that integrates quantitative design data generated from BIM models interacting with performance evaluation in a systematic way. It will give a better insight into the sustainable design process in the context of integration of BIM data and standard performance evaluation in the design stage.

2. Literature Review and Analysis

2.1. Infrastructure Sustainability and Sustainable Design. Elkington considered sustainability as a concept involving the famous triple bottom line—people, planet, and profit [5]. Abidin and Pasquire considered sustainability as an objective including elements of the design, such as energy efficiency, waste minimization, and low maintenance costs [6].

Sustainability is an important criterion in the construction of the infrastructures. The definition of sustainability in the construction sector has been discussed by many authors [7, 8]. Meng et al. referred infrastructure sustainability to life cycle sustained and effective system functionality for urban social, economic, and ecological development [9]. George et al. developed a 4Es (Economic, Effectiveness, Efficiency, and Ethics) and 4 Poles (Economic, Social, Environmental, and Technology) model of sustainability [10]. Similar pillars were also given by Hill and Bowen as social, economic, biophysical (the atmosphere, land, ecological community, and the built environment), and technical (the performance and quality of a building structure) [11]. Aksorn and Charoenngam grouped sustainability factors affecting local infrastructure projects into 6 dimensions: management and administration, information and knowledge, policy and plan, environmental and natural resources, facility and infrastructure, and finance and budget [12]. Booth et al. [13] and Black [14] defined the sustainable transportation system as encouraging recycling in its construction and minimizes and the use of land, minimizing the use of nonrenewable resources and reducing emissions and waste, allowing the basic access needs of individuals to be met safely while ensuring the health of people and the ecosystem, supporting a strong economy and facilitating equality between and within generations. In this paper, the definition of infrastructure sustainability is focused on assured compliance with conventional infrastructure sustainability specification in sustainability rating systems rather than proactive improvement of all sustainability factors.

Many researchers have suggested methods to achieve infrastructure project sustainability. Choguill summarized the 10 principle approaches used and evaluated by a number of countries to facilitate local infrastructure in a cost-effective and environmentally friendly manner in the planning, decision-making, implementation, and management processes [15]. The term sustainable construction was originally proposed to describe the responsibility of the construction industry in attaining "sustainability" [11]. Sustainable design was also adopted by many researchers [11, 16, 17]. They are often used in sustainability concepts.

2.2. Sustainable Infrastructure Rating Systems. The sustainability assessment of infrastructure projects plays a vital role in guaranteeing the success of projects. When examining the sustainability of infrastructure projects, many questions, such as what are the sustainability factors and how those sustainability factors can be measured, need to be subjected to more scientific scrutiny. Each dimension of sustainability should be evaluated. Koo et al. explored the interaction of all aspects of the project during the entire life cycle when conducting a sustainability assessment [18]. Shen et al. introduced a set of key assessment indicators to assess the sustainability of infrastructure projects in China [19].

Different methods are introduced to assess the sustainability aspects of the entire life cycle. Sustainable rating systems have been adopted for this purpose. There are more than 600 rating tools and about 170 evaluation criteria in the building industry [20, 21] such as Leadership in Energy and Environmental Design (LEED) in the US and Building Research Establishment Environmental Assessment Method (BREEAM) in the UK. There have been plenty of research on the interaction between BIM-based sustainability analyses and the building rating systems [22, 23].

Indicators for assessing the environmental, social, and economic performance of infrastructure are vague, and transport-specific sustainability metrics are more difficult to define than metrics for buildings. In the building assessment tool BREEAM New Buildings, for instance, thermal comfort is an aspect, but this aspect is not relevant for the infrastructure. Consequently, building sustainability rating systems could not be simply transferred to the infrastructure sector. Maybe because of this, the development of sustainability rating systems has been relatively slow for the infrastructure sector [24].

An example of a sustainability assessment tool for infrastructure is the Dutch system DuboCalc. DuboCalc is based on the "Assessment Method environmental Performance Construction and Civil engineering Works." This assessment method makes use of the Dutch "National Environmental Database" in which environmental properties of construction materials are stored. The assessment method is in turn based on the European norm EN 15804 "Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products." DuboCalc helps to assess the environmental impact of used materials during the whole life cycle, including winning raw material, transport, construction, operation, maintenance, demolition, and waste treatment. The resulting environmental performance of the construction project is subsequently translated into an environment cost indicator (MKI in Dutch), using a "shadow price method." In this way, the extra "cost" is defined as a result of the environmental impact of materials and structures. DuboCalc is mostly used in national infrastructure projects in the Netherlands.

Currently, a number of different rating systems are adopted to evaluate the sustainable performance of infrastructure [25]. These include but are not limited to the contents in Table 1.

Many of these systems were developed by or for specific agencies with a focus on specific, local environmental needs or context. Several local states and research organizations have set out to develop and implement their own rating systems to measure and quantify the sustainability of their own projects in a regional context. There is no current rating system developed and implemented by any national organization that can be compared with LEED and BREEAM.

Table 1: The state of the practice in infrastructure sustainability assessment.

Nations	Rating systems	Credit categories
United States	GreenroadsTM	Project requirements
		Environment and water
		Access and equity
		Construction activities
		Material and resources
		Pavement technologies
		Custom credits
	FHWA INVEST (infrastructure voluntary evaluation sustainability tool: sustainable highways self-evaluation tool)	System planning (integrate economic, natural, and social goals into long-range transportation planning, etc.)
		Project design (economic analysis, life cycle analysis, etc.)
		Operations (internal sustainability plan, energy use, etc.)
	STARS (sustainable transportation analysis rating system)	Project (integrated process, access, etc.)
		Plan (integrated process, community context, etc.)
		Safety, health, and equity
	GreenLITES (green leadership in transportation and environmental sustainability)	Sustainable sites
		Water quality
		Materials and resources
		Energy and atmosphere
	Envision sustainability rating system	Quality of life
		Leadership
		Resource allocation
		Natural world
		Climate and risk
United Kingdom	CEEQUAL (civil engineering environmental quality assessment and award scheme)	Project/Contract strategy (optional)
		Project/Contract management
		People and communities
		Land use (above and below water) and landscape
		The historic environment
		Ecology and biodiversity
		Water environment (fresh and marine)
		Physical resources use and management
		Transport
	HTMA-sustainable highways maintenance tool	Sustainable consumption and production
		Climate change and energy
		Natural resource protection and environmental enhancement
		Sustainable communities
Australia	Australian green infrastructure council-infrastructure sustainability (IS) rating system	Management and governance: management systems, procurement and purchasing, and climate change adaptation
		Using resources: energy and carbon, water, and materials
		Emissions, pollution, and waste: discharges to air, land, and water; land; waste
		Ecology
		People and place: community health, well-being, and safety; heritage; stakeholder participation; urban and landscape design
		Innovation
	VicRoads INVEST©–integrated VicRoads environmental sustainability tool	Air quality
		Behavioural change and capacity building
		Biodiversity
		Cultural heritage
		Energy
		Noise management
		Resource management
		Road design
		Stakeholder management
		Urban design
		Water and waterway
		Management

Issues related to water, energy, materials, and the environment are commonly identified between rating systems but different weights are given to each factor [26]. This checklist in rating systems could provide a foundation for digital sustainability assessment of infrastructures.

2.3. BIM and Infrastructure. The construction and maintenance of infrastructure have resulted in greater demand for natural resources, increased occupation of land, and in negative effects on the ecosystem. The inefficiencies and waste are in large part due to the lack of good quality information [27].

While 3D modeling is gaining increasing acceptance in building design and engineering, the infrastructure domain still heavily relies on 2D drawing-based processes [28]. However, recent research focuses on addressing these limitations by applying the 3D modeling paradigm to the infrastructure domain [29]. Referring to the best practices in the building sector, BIM is seen as a tool that improves efficiency and quality, reduces mistakes and rework, enables quantitative analysis, and facilitates effective communication. There are more research works and papers on 3D and 4D implementation in the infrastructure projects and the subject is highlighted in some pioneering reports [30]. Olde Scholtenhuis et al. adopted a 4D CAD-based method as a BIM tool to tackle coordination issues of urban utility works [31]. Hartmann et al. implemented BIM-based tools on a large infrastructure project, indicating that implementing BIM requires practitioners to align the BIM-based tools and well-established construction management work processes in a construction project [32].

Although BIM uses in infrastructure projects lag several years behind building construction, according to McGraw-Hill Construction [30], nearly half of the respondents (46%) report that they are using BIM on their infrastructure projects and 67% have achieved positive value. 78% of survey responders are using BIM on at least 25% of their infrastructure projects and these numbers will grow dramatically in the future. In Europe, the percentage of contractors that are using BIM on infrastructure projects (roads, bridges, tunnels, dam, and water) is growing in the UK (33%), France (19%), and Germany (16%), which is a little higher than that in the US (14%) [33]. More than half (55%) of the companies focusing on infrastructure projects in Australia and New Zealand claim to achieve over 25% return on investment (ROI) of BIM, whereas companies mainly doing buildings report a less positive ROI (only 29%) [34].

2.4. BIM and Sustainability. In the investigation of Bynum et al., most respondents indicated that BIM was used predominantly for the project coordination and visualization [35]. Sustainability was not a main application of BIM. BIM is mostly used for energy simulation of the building envelope (materials, lighting, and etc.). Kryegiel and Nies indicated that BIM can aid sustainable design in the aspects of building orientation, building massing, daylighting analysis, water harvesting, energy modeling, sustainable materials and site, and logistics management [4]. The majority of BIM tools capture three main engineering aspects: thermal load (heating and cooling) calculation, computational fluid dynamics (air flows in and around buildings), and interior lighting and acoustics simulation. The mature environmental analysis tools integrated within BIM tools have already been available in buildings.

Sustainability efforts are mostly based on quantifiable data, whether immediate or long-term, and BIM has the capacity to handle volumes of data. Apparently, sustainability elements in the BIM system lie in the inbuilt relationship and constraints, which improve the design and construction outcomes and provide a reasonable feedback loop from precedence [36]. BIM can be used to view and organize monitored data. For example, air-quality sensors can be placed in the facility to input data into BIM, resulting in the ability to monitor and analyze current conditions [37]. Ibrahim and Krawczyk have demonstrated the benefit of embedding building code requirements into the BIM software, making the review process much smoother [38].

Zahran et al. devised a new 3D visualization approach for modeling air quality before and after the implementation of potential urban transport schemes [39]. The European project Sustainable Energy management for Underground Stations (SEAM4US) developed an intelligent environmental aware energy management system for underground stations [40]. Yigitcanlar and Dur introduced the Sustainable Infrastructure, Land Use, Environment, and Transport (SILENT) model [41]. It is a GIS application for urban sustainability indexing and can improve the cooperation in decision-making among strategists, and planners bent on promoting sustainable development. All these approaches are useful for accessing the infrastructure sustainability; however, they disregard the support of scientific rating criteria like sustainable infrastructure rating systems.

BIM and sustainability are conceptually related and synergetic. Early integration of sustainability considerations into a policy and early involvement of BIM in the project development process is the key to ensuring that sustainable outcomes are achieved.

2.5. Literature Review Discussion: Identification of Research Gap. There is much research on the subject of sustainability and BIM in infrastructure projects separately. However, few authors highlight the contribution of BIM towards infrastructure sustainability, which can be seen as a lack of awareness of the potential of BIM as a catalyst to enhance sustainability and an unrealized relationship between sustainability vision and BIM objectives.

The design phase should be considered as the first stage for achieving sustainability [42]. Many studies have recommended that environmental issues should be fully incorporated into project planning and design to mitigate environmental impacts [43]. Embedding environmental knowledge contributes significantly to sustainable design. Sustainability analysis methods and criteria should be configured as early as possible without relying on detailed design information generated by the designers when discussed in detail in the paper [44].

Infrastructure sustainability rating systems contain all aspects of the infrastructure sustainability and their scientific relations. They can be used as benchmarks in order to compare different design choices and scenarios to support the decision-making and achieve continuous improvement. Creating BIM means creating the infrastructure digitally in the virtual environment, which needs to be linked with a database of project information. So in theory, any information required for testing "what-if" scenarios to better support the incorporation of sustainability and assessing of sustainability in the scheme is necessary.

There is little research bridging BIM model data and the early design stages in which information about sustainability decision-making factors run throughout the infrastructure life cycle. The successful implementation of BIM and sustainable building rating systems add heuristics to the integration of BIM and sustainable infrastructure rating systems.

3. Research Methodology

The paper is a qualitative research. As little theorization has been done on the BIM implementation on the infrastructure sustainability, we seek to contribute to the enrichment of the field by a literature review and interviews with representatives.

First, a thorough literature review of connections between three key topics (infrastructure, sustainability, and BIM) was carried out to follow the state of the art and identify the knowledge gap. A knowledge gap of lacking using BIM for infrastructure sustainability was identified. This problem can be overcome by the integration of BIM tools and sustainable infrastructure rating systems.

The interview method is a useful way to "learn from strangers" and obtain additional insights of interviewees' experiences [45, 46]. Interviews are often used to probe perceptions, attitudes, and experiences of participants in BIM research [47, 48]. Interviews with professionals from the academia and business were conducted for perceptions of the existing situation, and industry needs analysis. The informants were chosen because they have rich academic or industry experience and interest in applying BIM and sustainability concepts in infrastructure projects. Only firms that had completed at least one project using BIM tools were included. Twenty-nine interviews from Europe and China were conducted to fully reflect the current industry needs. The interviews were designed to probe their perceptions, attitudes, and experiences relating to the sustainability when implementing BIM in infrastructure projects.

A framework is often highlighted to organize domain knowledge and facilitate the elicitation of tacit knowledge [49]. Many BIM frameworks are introduced as a research and practical foundation for scholars and industry stakeholders [50, 51]. Findings from these two stages were used to conceptualize the framework that bridges the knowledge gap and satisfies the industry needs for integrating rating systems and BIM in the sustainable infrastructure design. Finally, a critical analysis and validation of technical requirements with part of the interviewed professionals in light of the industry needs were given. The technical requirements were categorized for the sustainability-supported BIM system as a reflection on the above framework.

4. Interview Research: Industry Needs Analysis

To define and design the framework for integrating BIM and sustainability rating systems, semistructured qualitative interviews with key players in the infrastructure industry were used to collect data. Of the firms included in the research, fifteen are based in Europe and fourteen are based in China, including Hong Kong. Of the informants in this study, there are three clients, fifteen designers/consultants, five constructors, and six researchers. Two clients, five designers/consultants, three constructors, and five researchers are from Europe and one client, ten designers/consultants, two constructors, and one researcher are from China. Details about the respondents are given in Tables 2 and 3.

4.1. Interview Results

4.1.1. Awareness and Interests. All of the respondents agreed with the national and international interests in the integration of infrastructure sustainability and BIM. The general revolutionary role of BIM is recognized and one or two examples of common BIM applications such as visualization and clash detection can be given easily. Regardless of the depth of the available BIM knowledge, their companies have started with the deployment of BIM and are eager to gain more experience and to make more breakthroughs in their projects.

However, only the group of the researchers who have studied the topic of sustainability and clients were well aware of the concept of infrastructure sustainability. Their understanding of sustainability was broader, containing environmental, economic, and societal aspects than practitioners. Designers, consultants, and contractors answered that they became aware of the importance of infrastructure sustainability, but they acted in their projects in a passive manner just following the existing regulations. In contrast, they were not always well aware and they usually had an incomplete understanding of sustainability.

4.1.2. Current Situation. This response to the interview showed that the integration of sustainability and BIM has not been evenly promoted over the whole construction sector. The awareness of the integration of infrastructure sustainability and BIM stayed at a lower level.

The biggest reason for this is the different focus of strategies and targets. The informants said that the main targets of sustainability in buildings were reductions of energy consumption and greenhouse gas emissions as a percentage over the baseline in the construction industry. However, the infrastructure is not an energy-intensive and greenhouse gas-emissive industry like building, but a material-intensive industry. In current strategies and targets,

Table 2: Overview of Interviewees: features of respondents in Europe.

No.	Role	Organization
1	Project manager	Government
2	Project manager	Government
3	Designer	Engineering consultancy
4	Designer	Architectural design firm
5	Designer	Architectural design studio
6	Consultant	Architectural design studio
7	Consultant	Infrastructure consultancy
8	Project manager	Contractor
9	Project manager	Contractor
10	Project manager	Contractor
11	Researcher	Consultancy
12	Researcher	Applied scientific research institute
13	Researcher	University
14	Researcher	University
15	Researcher	University

Table 3: Overview of Interviewees: features of respondents in China.

No.	Role	Organization
1	Client	University
2	Designer	Architects and engineering institute
3	Designer	Municipal engineering design institute
4	Designer	Design and research institute
5	Designer	Architectural and civil engineering design firm
6	Consultant	AEC technology company
7	Consultant	Engineering consultancy
8	Consultant	University
9	Consultant	AEC technology company
10	Consultant	Engineering consultancy
11	Consultant	Research Institute of Building Science
12	Project manager	Contractor
13	Project manager	Contractor
14	Researcher	University

material and resource targets are not suggested for the infrastructure industry.

Because of the late dissemination of BIM in the infrastructure, it is still in an early phase to evaluate the achievement of the integration of infrastructure sustainability and BIM. The informants gave the positive view that BIM had attracted a big amount of attention in the infrastructure industry. However, the informants gave the negative view that the current policies of sustainability have not led to the change for the integration of sustainability and BIM.

4.1.3. Barriers

(1) Government Agencies' Willingness and Effort. The informants pointed out the unsystematic policy by the government as one of the biggest barriers. In fact, the government provides enormous efforts for BIM and infrastructure sustainability but fails in less apparent criteria in a passive manner. The government just encourages public building sectors to reduce energy and greenhouse gas emissions. When it comes to the infrastructure, there are no determined goals and guidelines. In the future, more and more public projects are required to use BIM. But the definition of using BIM is so vague that it is unclear whether sustainability will be addressed as well. Less systematical criteria in policy and less apparent standards cause the industry to be doubtful about the way forward to the integration of infrastructure sustainability and BIM.

(2) Client Attitude. One of the critical reasons for the low interests is the initial and additional cost for the integration of infrastructure sustainability and BIM. Every participant has a goal in terms of creating profits from their projects. Higher sustainable requirements and BIM investment can increase cost when the work processes are changed and new software must be acquired continuously. When talking about the performance assessment, cost, time, and quality are always important subjects and often also customer value and environmental issues. Due to the complexity in sustainability analyses, designers usually choose manual calculation, with traditional paper maps, unless a special team for sustainability is assigned. It takes time, skills, and efforts of architects to submit a sustainability report. It is not easy to see how BIM is paying off.

(3) Performance Evaluation. When the policy for green building was established, the policy was evaluated with relevant methods like LEED or BREEAM to meet the utmost vision and goal. In a similar manner, the policy of sustainable infrastructure needs performance measurement. The informants pointed out that the necessary criteria and performance measurement tools for sustainable infrastructure are still missing. When asked about their efforts in carbon emissions reporting and reduction, most of the informants hummed and hawed, giving no definite reply. Voluntary sustainability targets have proven elusive and there is much more to be done.

(4) Supply Chain Integration. Supply chain partners are challenged to identify sustainable alternatives both in the upstream and downstream processes. If the client has no ambition for BIM and sustainability, the designer may choose a traditional approach and ignore the consideration of sustainability. If the designer has not put the concept of BIM and sustainability in the plan, the contractor has only limited possibilities to deliver sustainable construction. If there are no efforts from the upstream, it is quite difficult for the asset manager to achieve sustainable development in the BIM way.

(5) Sustainability Knowledge and Expertise. Sustainability is hard to define and can be seen as a vague concept. Most informants confirmed that currently the integration of infrastructure sustainability and BIM is not clearly defined. BIM for environmental infrastructure sustainability is not known amongst the informants. Some were very enthusiastic. Others were more cautious, stating that there are many parameters that determine sustainability, but not all of these factors are taken into account by BIM. Moreover, there is not much willingness to document lessons learned

from infrastructure projects for sustainability as confirmed by the experience shared by a few informants.

There is still not a clear and consistent understanding of the concept among practitioners and academia in this survey. The academics were ambitious for taking sustainability into consideration and were not satisfied with the carelessness of the industry. The informants from the industry had different views on sustainability. Most of them had not realized that BIM has the ability to facilitate the infrastructure sustainability. Sustainability becomes a byproduct rather than becoming the main goal of BIM. This knowledge gap between the academic and the industry will limit the promotion of BIM.

(6) BIM Technology Readiness Level. The paradigm of integration of infrastructure sustainability and BIM stays in the beginning phase. Informants from the client insist most of the data for sustainability are stored in GIS databases. BIM and GIS are not always compatible. The approach for harmonization of BIM and GIS is still discussed. This means that BIM cannot fully support the sustainable solutions from the perspective of technology. BIM is still mainly seen as a tool for visualization by most respondents. With regards to BIM, most participants agree that the available software is currently less focused in the infrastructure construction.

4.2. Summary. In this section, the results of a number of interviews with stakeholders are presented. The results represent the opinions of the stakeholders about the integration of infrastructure sustainability and BIM. The informants expressed that there are pros and cons of the current status of the sustainable infrastructure design and BIM. The interview results confirmed that BIM implementation was encouraged not only for its efficiencies but also for environmental reasons. After analyzing the responses of different types of informants (clients, designers/consultants, constructors, and researchers), gaps in practices were revealed, which are discussed from the categorization of barriers in key thematic areas. Together, these barriers have an impact on the infrastructure sustainability and BIM. The interview data suggest that the integration between BIM and sustainability evaluation criteria should be established.

5. Framework for a Sustainability-Supported BIM System

In this section, a theoretical framework for a sustainability-supported BIM system is presented. The main elements of the framework are presented in 5.1, followed by a high-level architecture in 5.2.

5.1. Framework Elements. As shown in Figure 1, the proposed framework consists of three major components: BIM model user interface, sustainability rating processor, and sustainability rule database. They are interrelated with each other in a way that data are shared in an automatic and efficient way.

5.1.1. BIM Model User Interface. Given a large amount of environmental data that need to be compiled for effective suitability analysis in sustainable infrastructure rating systems, BIM is used as an effective tool for organizing, storing, analyzing, displaying, and reporting the information.

The basic skeleton of the framework is based on the infrastructure BIM model in BIM model user interface. BIM model user interface allows designers to input the basic information of an infrastructure project. Data stored in a well-established BIM model provide enough information and specialized expertise to complete such a computationally complex rating and analysis, for example, materials and resources in GreenLITES (Green Leadership in Transportation and Environmental Sustainability) and using resources: energy and carbon; water; materials in Australian Green Infrastructure Council—Infrastructure Sustainability (IS) Rating System. Another feature of the BIM model user interface is the provision of the evaluation results. A snapshot of the evolving design object is defined without complicated data for subjective sustainability-related decision-making. The user interface can interact with the BIM model to generate real-time visualization.

5.1.2. Sustainability Rule Database. As the second component of the framework, the rating systems are used as the design criteria for choosing the best program or checklist of the sustainability factors. Sustainability rating systems are suitable tools for assessing an infrastructure's environmental performance. The existing sustainable infrastructure rating systems have covered almost every aspect of sustainability in the domain of the infrastructure. A defined list of indicators cannot make a future-proof assessment system. The rules in a sustainable infrastructure rating system are often expressed in a natural language such as quality of life in envision sustainability rating system. To convert the rules into a database, the conditions and properties from the rules should be extracted and all properties contained in the rules should be distinguished. BIM appears as a good resource for providing the needed information. Digital mechanisms of BIM will help enhance its usability to the maximum level.

5.1.3. Sustainability Rating Processor. The sustainability rating processor contains all the evaluation formulas, extracts the required information from a BIM model, and calculates the value demanded by rating systems. On the other hand, the sustainability rating processor can retrieve the evaluation results from the sustainability rule database and display the results in a BIM model with highlighted elements.

Sustainable infrastructure rating systems require significant amounts of specific information typically carried within BIM design tools, but they are not able to communicate easily and efficiently with existing BIM authoring tools. Only the particular BIM data contain the necessary information to perform corresponding performance simulations. Therefore, the function model extractor is needed.

Ideally, the designer could directly access the data of the BIM model, but the rule compatibility can be highlighted as

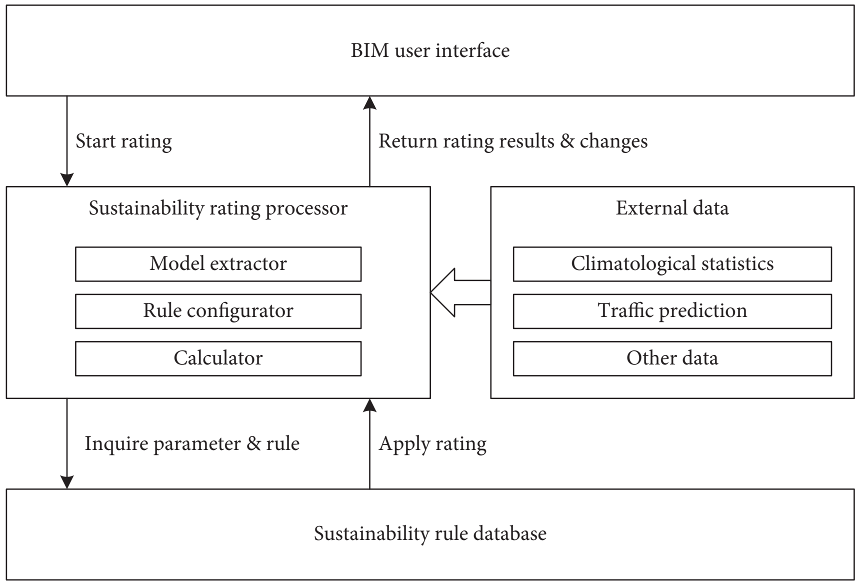

Figure 1: A framework integrating BIM and sustainable infrastructure rating systems.

one of the main difficulties involved in current rating systems. This can be solved by the function rule configurator. BIM models can be comprehensive including sustainability-related requirements and can be checked for compliance with sustainability.

A comprehensive assessment of all aspects of sustainability requires an evaluation to determine whether sustainability has been sufficiently incorporated into the plans. This process is carried out by the function calculator.

However, besides BIM models, other kinds of external data are required as supplementary elements. The input data to the sustainability rating processor is supplemented by another component—the external data. The meaning of external data here is broad enough to cover climatological statistics (climate change in HTMA-sustainable highways maintenance tool), traffic prediction (transport in CEEQUAL), and so on. Different types and numbers of external data can be multiplied and expanded to the urban level in support of the infrastructure quality. Correlations can be analyzed between the external data and the design quality in the framework of sustainability rating systems.

5.2. Framework Design

5.2.1. Architecture. Learning from experiences from sustainable building design, two lessons are drawn. In order to deliver sustainable design, the first way is to optimize the energy use and material consumption in a certain built environment, and the second way is to try an alternative new method which is more cost-effective than the original one. The former way depends on a computational test using large quantities of data from the design, whereas the latter way needs a quick what-if scenario visualization. The proposed BIM-based sustainable performance calculation framework is based on three components:

(1) BIM user interface which supports 3D object-based BIM models with an underlying database of component information,

(2) sustainability rule database which contains all the items in the checklist in sustainable infrastructure rating systems, and

(3) sustainability rating processor that is accessible from the BIM software platform and from infrastructure sustainability rating systems, and the external data excluding the categories contained in the BIM software platform but required in the sustainable performance databases.

Six major steps of BIM analysis for sustainability issues in the guidance of sustainability rating systems include (but not limited to) the following:

(1) definition of the proper parameters and rules for the analysis,

(2) definition of data needs,

(3) acquisition and extraction of data, including external data, if necessary,

(4) configuring BIM models containing the data with rules from the sustainability rule database,

(5) applying to rate and return results, and

(6) refinement of the model.

Following the above principles, a framework integrating BIM and sustainable infrastructure rating systems is developed as shown in Figure 1.

Take FHWA INVEST (infrastructure voluntary evaluation sustainability tool: sustainable highways self-evaluation tool) as an example. The Sustainability rating processor implements the sustainability rating with the help of the model extractor to extract needed data from the BIM model. To facilitate infrastructure sustainability rating, the rule rating process is separated into three functions: the model extractor for model preparation, the rule configprator for rule interpretation, and the calculator for rule execution. These three components are highly interrelated to construct a systematic view of the sustainable design.

This rating system has three main rules: system planning, project design, and operations. The rule configurator facilitates the management of rules. It serves as the connection between BIM models and the sustainability rule database. It helps establish the consistency of an infrastructure element's functional and physical attributes with its sustainability requirements and convert standards into rules readable by BIM models. Some analysis can be done directly (economic analysis in project design). The query methods are stored in XML format. Such capabilities are already available through gbXML (the Green Building XML schema), which helps facilitate the transfer of properties stored in BIM models to energy analysis tools (life cycle analysis in project design and energy use in operations). In the framework, the BIM model needs the addition of the climatological statistics (natural goals in system planning), traffic prediction (long-range transportation planning in system planning), and other data to be used as a source for rating. The external data hold one of the key positions in the integration. The calculator uses parameters and rules in the sustainability rule database and organizes BIM model data to perform compatible rule evaluations and then sends the evaluation results to the BIM user interface. Then, the rating results are sent as a conclusion to the BIM model user interface for visualization. Through the BIM model user interface, the evaluation result can be illustrated in both the BIM model and data tables for assisting sustainable infrastructure design.

The decision-making activity will be based on the configured model under the assessment of the chosen sustainable infrastructure rating system. If there is still lacking information for evaluation and decision-making, the model extractor will trace back from the original BIM model and the external database. If decision-makers are not satisfied with the results, the sustainability rating processor will go back to where the environment is saved, thereby permitting the correction of a previous plan. After several loops, the best-performed model can be selected as a candidate for the further development.

5.2.2. Operational Mechanism. The dynamic changes are not considered in the traditional method. BIM provides a platform capable of capturing these dynamic data affecting the performance and level of service in infrastructure projects. The architecture of the framework, in reality, forms a learning cycle for critical thinking. Figure 2 illustrates the sustainable design cycle. The original design program is translated into BIM models and these BIM models then act as the raw information on which decisions are based. Related rating systems and local environmental data are processed to orient for further analysis and revision. The same loop and logic are repeated continuously until the optimal decision is obtained fully conformant with these standards requirements. Finally, infrastructure design decision-makers gain an advantage of full awareness of the situation and flexible fitting the local sustainability rating system.

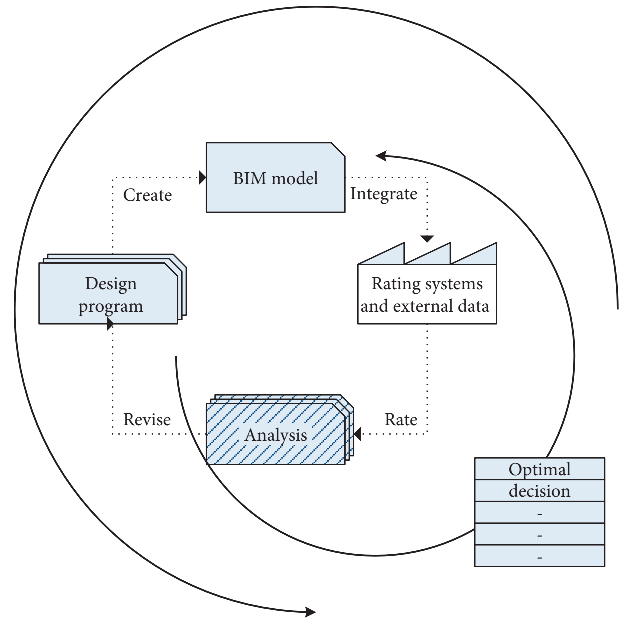

Figure 2: Sustainable infrastructure design cycle.

Continuous addition of external data and evaluation can directly go back to the design phase data and decision-making moments with ease using this framework. By upscaling to multiple project sites in an urban context, the framework can integrate both rich local environmental data and custom-made sustainability rating systems to monitor and analyze the sustainability performance of the infrastructure project. The framework also enables tracing back to the design data of certain time, in order to continuously improve decision-making in the infrastructure life cycle management. In this way, the integration solution aims to change the sustainable design from a linear process to an iterative and continuous process.

6. Framework Validation and Technical Requirements

The prototype of Figure 1 was validated by an additional dialogue with the interviewed professionals who expressed their interest in the potential framework in the prior interviews. The validation showed that the framework adequately responds to the needs of the current industry because it helps to make more informed decisions and to have all the information needed in one place. In addition, respondents highlighted the time savings in the sustainability checking and the possibility to store, organize, and classify information, and considered it as a good guide for the decision-making process, decreasing the likelihood of making a wrong decision in this way.

6.1. BIM Model Management Related Requirements

6.1.1. Data Repository. The data capacity and efficiency of the framework rely on the full access to the data repository.

Different parts of the infrastructure can be modelled with different BIM authoring tools. These federated data repositories should be linked to each other. The sustainability-supported BIM system should be supported by a centralized data repository of the infrastructure project.

6.1.2. External Data Access. Projects tend to be run under large document management and approvals systems. The CAD or BIM data are only one part of the total information store. The large scale of these projects tends to demand integration with GIS and mapping type information. Architects can input supplementary data into the BIM models that help the design team understand issues related to the climate, location, and surrounding environment.

6.1.3. Interoperability-Based Specifications. Interoperability-based specifications allow each object to be uniquely identified, preventing misunderstanding, confusion, and duplication. IFC is the only nonproprietary intelligent, comprehensive, and universal data model for built assets [52]. However, IFC files only contain the information that was processed at export and has the potential loss of information during export [53]. The sustainability-supported BIM system should enable efficient integration to interact between different discipline-specific models.

6.2. Sustainability-Related Requirements

6.2.1. LCA-Based Calculation Rules. Sustainable infrastructure rating systems facilitate to consider decisions and activities which occur during the life cycle of a project. It applies to a broad range of transportation life cycle phases or to focus primarily on one or two phases [54]. Design and realization choices have a significant effect on the environmental impact of infrastructural works. Therefore, the ICT tool should be developed to calculate the environmental impact of the different infrastructure designs, based on material and energy use during the whole life cycle.

6.2.2. Customized Scorecard. In practice, team members need to determine whether the given criteria are relevant to the project and whether they should be used in rating. The framework should allow rules that do not apply to a given project to be removed from the total amount of possible points. Sustainable infrastructure rating systems facilitate the assignment of weights to various criteria or allow the user to apply customized credit weights when evaluating the sustainability of the project [54]. This should be embedded in the rule configurator of the framework.

6.3. Implementation Issues. According to the analysis before, one infrastructure sustainability rating system that can integrate it all is impossible. So locally used BIM software/platform for sustainability capability should be developed. Checking the infrastructure design models for compliance with sustainability rating systems must be developed further.

The baseline of the infrastructure performance shall be generated by simulating the infrastructure with its actual orientation. BIM software companies can develop sustainable infrastructure rating system code-checking software plug-ins embedded in BIM software tools. Compared with outsourcing to a third party to conduct the environmental analysis independently, it is beneficial for designers to receive feedback directly from the BIM model user interface and improve their designs continuously.

7. Discussion

7.1. Theoretical Implication. Interviews with professionals in this research demonstrate that the use of rating systems to attain higher degrees of sustainability is certainly becoming more commonplace than ever before. The benefits of BIM pertaining to productive data storage and data computation are greatly advantageous throughout the design processes. This study complements the current literature by indicating that rating systems and BIM extends the designers' perception via evaluation, navigation, and simulation, and at the same time offers alternative ways of understanding the sustainability, as current assessment methods for infrastructure sustainability are often based on the designer's judgment [55]. This study contributes to the sustainability and BIM research in infrastructure projects by presenting a theoretical framework. The framework enriches the body of knowledge of green BIM. Prior studies have found that green BIM can enhance the environmental sustainability of buildings [56, 57]. We seek to contribute to the enrichment of the field by building conceptual bridges between rating systems and BIM in the infrastructure design.

7.2. Practical Implication. The research provides a new perspective in managing the BIM data of infrastructure projects. The framework for a sustainability-supported BIM system opens the door for more integration of BIM in the infrastructure sector. It helps to enhance environmental management performance of infrastructure projects as they can base their work on the analysis of sustainability in the design stage and as they progress. Rating systems and BIM are suggested to be integrated into the infrastructure design, which provides the ability to better analyze and visualize the data infrastructure projects [58]. A more proactive attitude toward sustainability and more powerful BIM data processing capability is essential to achieving the combination in infrastructure projects [59].

7.3. Limitations and Future Research Directions. The paper opens the area for further research but it is not yet ready for implementation in practice. The future integration of BIM and infrastructure sustainability rating systems will be completely interactive with key infrastructure information, climate information, traffic requirements, and environmental impacts. Then, once the infrastructure is completed, the BIM model will create an opportunity for the asset management feedback loop. The proposed framework is conceptual in nature but provides the underlying foundation for infrastructure designers to consider how BIM can lead to a sustainable advantage.

8. Conclusion

As with earlier studies on literature and interviews, this study found that people are interested in the effect of BIM for infrastructure sustainability. However, BIM is used for design and construction management more often but not necessarily for sustainability purposes. This research proposes a theoretical framework for a sustainable design approach for integrating BIM rating with sustainability rating systems. From a theoretical viewpoint, the underlying premise of the proposed framework introduces a new paradigm for the sustainable design of infrastructure. The proposed framework will enhance the sustainability-supported BIM system research and development and better promote intelligent and automated sustainable design. One of the key contributions of the framework is to propose a process in which BIM is used as an accelerator for innovation in the infrastructure project sustainability improvement. The framework especially focuses on the integration of various static (rating systems) and dynamic (BIM) data in terms of sustainable design decision-making considering environmental sustainability. Another contribution is the integration of sustainable infrastructure rating systems and the feedback loop to accelerate optimal decision support. It provides an insightful view of the infrastructure design process with the aid of BIM tools and rating systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Previous versions of this paper were presented at the CIB W78 conference 2015.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Traffic Allocation Mode of PPP Highway Project: A Risk Management Approach

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Highway projects are the favorites of public-private partnership (PPP) investors because of their stable cash flow. However, there are high uncertainties in terms of traffic volume, resulting in unpredictable revenues, which has drawn major concern of PPP investors. For a road in a network, the traffic volume is determined by the traffic allocation rate, which is affected not only by the total traffic volume in the region but also by other traffic risk factors, such as travel time, toll rates, and travelling comfort. The conventional traffic allocation forecasting technique predominantly depends on the travel time, overlooking other risk factors. Consequently, traffic allocation forecasting is usually inaccurate. To improve the accuracy of traffic allocation forecasting in PPP road projects, this paper proposes to consider the effect of traffic risks together with traffic time by using the mean utility. Multinomial logit (MNL) model based on mean utility is used to predict the traffic allocation rate. To validate the proposed model, the system dynamic (SD) modeling is established to forecast the traffic volume of a case highway using the proposed traffic allocation forecasting model. The simulated result shows that the simulated traffic volume of past years from the proposed model is highly consistent with the actual one, evidencing that the proposed model can greatly improve the accuracy of the traffic forecasting.

1. Introduction

PPP investors prefer highway projects because of their stable cash flow and relatively low level of competition. The early highways, such as Guangshen Expressway in China, Bangkok Expressway in Thailand, and the North-South Expressway in Malaysia, were all built via a built operation transfer (BOT)/public-private partnership (PPP) scheme. However, many early BOT/PPP projects including highway projects in China were stopped by the central government in 1999 due to unfair contract conditions [1]. To accelerate the development of new highways and to facilitate the national expressway network in China, the Traffic Financing and Investment Company has been established to finance highway projects through toll collection. Under this scheme, highway development has been greatly accelerated. By 2015, the highway mileage has reached 120000 km [2]. However, because the actual traffic volume of some highways is less than the predicted value [3] and the construction speed is high, the debt of local governments has dramatically increased. According to the Ministry of Transport of the People's Republic of China, the gap between the debt and the revenue reached RMB 318.73 billion yuan in 2015 [4]. To relieve pressure of the local governments, the State Council released "Guidelines for Improving the Management of Local Government Debt." The investment from enterprises, both state owned and private, is then reencouraged to invest into highway construction using a PPP scheme under the provision of concessions. Construction is a risky business, especially in infrastructure projects [5, 6]. One of the important reasons of early unsuccessful BOT/PPP projects is the negligence of the demand risks. Therefore, the traffic volume is always will be the most critical risk to the return of investment.

Some studies have investigated the traffic volume risk from the perspective of risk management. Ashuri et al. [7] pointed out that uncertainty about future traffic demands is one of the most significant risks during the operation phase of BOT projects. They applied the real options theory to determine the minimum revenue guarantee (MRG) option price in BOT projects. Iyer and Sagheer [8] adopted the model concession agreement (MCA), a standardized risk allocation framework, to treat risks for BOT highway projects in India. If the actual traffic volume deviates from the projected traffic, the MCA suggests varying the length of the concession period by a preagreed formula to mitigate the traffic demand risk. To avoid gaining excess profit or being unable to get the expected profit in the situation where traffic demand deviates from the expectation, Song et al. [9] discussed the single adjustment and linkage adjustment on toll rates and concession period. These studies predominantly focused on the quantitative impact analysis of traffic risk on other factors. There is little literature discussing the impact of other factors on traffic volume risk, although they are actually interactive.

Traffic volume risk has been discussed in the context of Traffic Engineering. Apronti et al. [10] estimated traffic volume on Wyoming low-volume roads using linear and logistic regression methods. Xiang [11] proposed a road impedance model based on the traditional Green shields linear model of traffic wave theory. Soliño et al. [12] measured the uncertainty of traffic volume on motorway concessions by using a time-series model. Song et al. [13] improved the dynamic road impedance function based on traffic wave theory. Liu and Chen [14] deduced the relationship between link flow and travel time in congested and noncongested conditions based on the Edie model. However, these studies mainly discuss the influence of travel time on traffic volume, ignoring other risks, such as users' willingness to pay, high toll rates, and long concession period of PPP highways projects.

To analyze the impact of other risk factors on traffic volume, risk assessment is necessary. According to *Risk Management: Principles and Guidelines* (AS/NZS ISO31000, p. 18) [15], "Risk analysis can be qualitative, semi-quantitative, or quantitative, or a combination of these, depending on the circumstances." Although statistical analysis is ideal for quantitative assessment, most risks in PPP projects are difficult to quantify because the underpinning information is usually unavailable or insufficient. Therefore, qualitative risk assessment has been mainly conducted. In the early stage, Wang et al. [16] evaluated risks by using the 5-scale method. Kuchma [17] put forward a fuzzy way of measuring the criticality of project activities. Recently, Xu et al. [18] set up a fuzzy synthetic model which could be directly used for PPP highway projects. Li and Zou [19] developed a fuzzy AHP-based risk assessment methodology for PPP projects. Ning and Zhao [20] established a risk assessment procedure through expert interviews and two-round Delphi. Wang et al. [21] applied the theory of real option and the theory of the bargaining game to assign the option value between two parties and to establish the distribution principles of PPP projects in terms of excess return. Wu et al. [22] assessed the risks in PPP straw-based power generation projects using the fuzzy synthetic evaluation method. However, Walker and Smith [23] pointed out that, by studying the magnitude of the possible impact that may be caused by contingent factors, the parties can better allocate the risks through contract clauses, procurement of insurance, or other risk response measures. Ng and Loosemore [26] also pointed out "there is considerable evidence to suggest that risk transfer is often handled poorly between parties to many PPP projects. For a host of reasons, parties to concession projects take risks which they are not clear of, or they are not able to cope with, or they do not have the appetite for and cannot charge for." Thus, a carefully prepared quantitative risk analysis is necessary to produce more positive and rational risk-taking attitude if the risk-taking parties know where they stand.

To improve the accuracy of forecasting the traffic volume, the road allocation rate is the key. This paper proposes to predict the traffic volume by considering the effect of risks on the traffic allocation rate. Firstly, the recent PPP highway projects are analyzed to identify the main risks affecting the traffic volume. The effect of the traffic risks together with traffic time is considered by using the model of mean utility of users. Then, the MNL model based on mean utility of users is proposed to compute the traffic allocation rate. To determine the effect of risks on traffic allocation, they are quantitatively measured using multiple linear regression analysis with SPSS based on the questionnaire. Finally, system dynamic (SD) models of the proposed traffic allocation model were established to validate the model by comparing the simulated traffic volume of past years of a case highway with the actual volume.

2. Case Analysis of PPP Highway Projects

For discussion, the PPP highway projects cover the roads and bridges in this paper. Investors gain returns of investment (ROI) by collecting tolls. Seven BOT/PPP highway projects were selected to analyze the related risks (Table 1). These projects spread across China, namely, cases 1, 3, 4, and 5 in the east part, case 2 in the south part, case 6 in the north part, and case 7 in the west part. They are built at different stages of PPP development in China and invested by various sources. In China, BOT/PPP projects were invested by investors from abroad and Hong Kong before 1999 [1]. Cases 2, 4, 5, and 6 were executed before 1999 and invested by Hong Kong investors. After 1999, BOT/PPP projects were invested by mainland investors (because the fixed return condition to investors was not allowed in concession contracts and loses the attraction of foreign and Hong Kong investors by then); cases 1, 3, and 7 were after 1999. Although the location, execution time, and investors of these projects are different, they all encountered common problems. Some stopped the contract at the compensated return much lower than the promised fixed return rate in the concession contracts. Some are in operation, but opposed by users because of the traffic congestion and/or high toll rates. The qualitative risk analysis (Table 1) shows that traffic volume risk is the most common risk, appearing in five projects in two ways: insufficient traffic volume and underestimated traffic volume. Other risks include high toll rates, long toll collecting period, public opposition, traffic congestion, poor

Table 1: The qualitative risk analysis of the PPP highway projects.

Number	Project name	Case description	Risk analysis
1	Hangzhou Bay Sea-Crossing Bridge	The projected traffic volume was 14.152 million vehicles in 2008. But the actual traffic volume was only 11.124 million in 2010 and 12.524 million in 2012. The actual traffic volume varied significantly from the projected value in the feasibility study report in 2003. The toll as the only source of income was 643 million yuan in 2013, a return on investment of 4%. It was far less than 12.8% as projected. In July 2013, the second crossing-sea bridge Jiashao Bridge over Hangzhou Bay was open to the public, decreasing the revenue further.	Insufficient traffic Competitive road diversion
2	Guangshen Highway	The traffic on Guangzhou-Shenzhen Expressway is always heavy and congested, causing traffic accidents. The revenue has exceeded greatly than predicted since its open to the public. The high return on investment had drawn public concern where cutting the charge level has been strongly advocated. Poor road conditions, serious congestion, and high tolls had become its major criticisms.	Underestimated traffic Poor road conditions Traffic congestion High toll rate Public opposition
3	Nanjing Third Yangtze River Bridge	Nanjing Third Yangtze River Bridge was designed to attract the traffic from Anhui Province to Jiangsu Province. The traffic to and from Anhui is for free on Nanjing First Yangtze River Bridge. In 2007, there were only 15,000 vehicles per day while the traffic of Nanjing First Yangtze River Bridge was 60,000 vehicles. With the continuous improvement of the surrounding road network, more traffic would be diverted. The future of the Third Yangtze River Bridge is not optimistic. Therefore, the toll rates of the Third Bridge were cut down to attract vehicles. However, drivers still preferred going through crowded but free Yangtze River Bridge. As a result, the toll collecting period was officially extended from 25 years to 30 years. The public strongly opposed the period change and questioned constantly.	Insufficient traffic Competitive road diversion High toll rate Long toll collecting period Public opposition
4	Fujian Quanzhou Citong Bridge	Before the construction of the Citong Bridge, there is the Quanzhou Bridge over Jinjiang. Before 1997, the revenue of Quanzhou Bridge was handed to the provincial treasury. So Quanzhou municipal government strongly supported the construction of the Citong Bridge. However, in 1997, the provincial government transferred the operation of Quanzhou Bridge to the Quanzhou municipal government back. The original annual income of Quanzhou Bridge was 50 million. After the completion of the Citong Bridge, the traffic of Quanzhou Bridge suffered steep losses. Its annual income plunged to 30 million. The Citong Bridge and the Quanzhou Bridge became direct competitive bridges. Thus, the existing of Citong Bridge had threated the benefits of Quanzhou Bridge.	Insufficient traffic Competitive road diversion Lack of government credit Incorrect prediction of traffic volume
5	Xinyuan Fourth Minjiang River Bridge	Fuzhou municipal government has explicitly guaranteed that all vehicles from the south gate of Fuzhou would go through the Xinyuan Fourth Minjiang River Bridge for 9 years since it was opened to public in 1997, with an annual net ROI of 18%. However, in May 2004, Fuzhou second ring road opened whose access was less than two hundred meters from Baihuting toll stations. Since then, many vehicles bypassed the toll stations to go through the free second ring road, resulting in a sharp decline of the revenue of the fourth bridge. Given no further negotiations were approved, the private sector applied for arbitration.	Insufficient traffic Fixed returns Competitive road diversion Public opposition Lack of government credit
6	Hebei Fude Highway	The Fude Highway was located on the traffic arteries. Its actual traffic growth was far beyond the predictions. In the 8th year, the total investment had been recovered. In addition to operation cost and tax, the operation of the remaining decade is very profitable.	Underestimated traffic volume Long toll period
7	No. 2 and no. 3 Xianyang Wei River Bridge	There are 4 bridges on Wei River in Xianyang. No. 2 and no. 3 were built under the BOT scheme. The average daily traffic in Xianyang City was 100,000 vehicles. Many drivers chose no. 1 Xianyang Bridge as it is free. It caused high traffic pressure and congestion in the city of Xianyang. The public has been requesting the cancellation of tolls at no. 2 and no. 3 bridges to ease the congestion. On May 1, 2011, the municipal government decided to buy back the operation of two bridges. This caused 750 million loss for the investors.	Public opposition High toll rate

road conditions, competitive road diversion, and lack of government credit. Most of these risks are closely related to traffic volume except the lack of government credit. It should also be noted that although competitive road diversion may result in insufficient traffic, it will not be considered in this paper because it is out of control of project mangers and may be considered in further study.

The risks under consideration can be divided to different classifications. High toll rates, long toll collecting period, and public opposition decrease users' willingness to pay. Traffic congestion and road conditions affect actual travel time and comfort level. When the congestion of a road is serious and road conditions deteriorate, travel time is extended, and the comfort level goes low. Thus, we divided the risks to three categories: travel time, willingness to pay, and comfort level (Table 2). It should be noted that though willingness to pay and comfort level have the same risk factors, they are different effects both caused by the same two factors. Thus, they were treated as different risk categories' in this paper. In traditional traffic forecasting theories, travel time is the determinant to decide the traffic allocation rate. This paper improves the forecasting method of traffic allocation by considering not only travel time but also users' willingness to pay and comfort level (Table 2).

Table 2: The risks related to traffic allocation rate.

Categories of risks	Travel time	Willingness to pay	Comfort Level
Risk factors	Traffic congestion and poor road conditions	High toll rates, long toll period, and public opposition	Traffic congestion and poor road conditions

3. Research Methodology

In traditional traffic allocation theories, the road impedance which refers to the sum of travel time and intersection delay is the most important key parameter. It directly determines the road choice and the traffic allocation. The most typical road impedance functions are Bureau of Public Roads (BPR) function, logit delay function, Akcelik delay function, and EMM/2 tapered delay function [27]. However, they only consider the time-related parameters and overlook the social and socioeconomic factors such as users' willingness to pay and comfort level of a road. As a result, the traffic allocation rate cannot be forecasted accurately based on these functions.

To predict the traffic volume more accurately, flexible demand forecasting methods have consequently been sought, particularly those capable of incorporating the behavioral forces linking individual transportation decisions and the relationships between individual travel choices and aggregate flows. The individual travel decision is determined by travel time, user's willingness to pay, comfort level, trip purpose, etc. Therefore, the route choice of users is not only based on travel time but also on socioeconomic factors.

In the model of consumer behavior in traffic area, consumer behavior is elaborated to focus on the relationship between consumer behavior and transportation. The traffic consumer is assumed to have a utility function bearing both consumption and transportation attributes. The individual's decision on route is affected by the attributes of transport modes, such as travel time, but also by usual budget constraint, the willingness to pay, etc.

A disaggregate choice model is defined by specifying a probability distribution for some unobserved variables (such as willingness to pay), given the values of observed variables (such as travel time and comfort level) in a homogeneous market segment. This probability distribution determines the choice probabilities and the proportions of the group with maximum utility for each alternative.

The multinomial logit (MNL) model of choice probabilities, viewed as a functional form for alternative (mode) not necessarily a behavioral relationship, has been widely used in transportation planning [25]. It can be derived from the theory of individual choice behavior by assuming that individual utility deviates from mean utility. Mean utility is defined to be the average of the utilities of all individuals in a homogeneous market segment and is viewed statistically independent for different alternatives.

The components of the utility function are consistent with the risks influencing the traffic volume, including consumption and transportation attributes. Thus, the MNL mode is chosen to compute the traffic allocation rate in this research.

3.1. Mean Utility of Users of PPP Projects. McFadden et al. [24] created the average utility formula (1) which can more realistically reflect the aggregated effect on users' choice of road:

$$V_i = -b_T \cdot T_i - b_C \cdot C_i + b_A \cdot A_i, \tag{1}$$

V_i is the mean utility of the road i; T_i is the travel time of the road i; C_i is the travel cost of the road i; A_i is the comfort level of the road i; and b_T, b_C, and b_A are undetermined parameters, on behalf of the marginal utility of each variable.

In formula (1), the mean utility refers to the accumulated psychological experience of public after undergoing a series of favorable and unfavorable factors during use. It is a measure of the satisfaction to the convenience requirements, consisting of travel time, travel cost, and convenience. As the time and cost impede users' convenience experience, they are negative variables in formula (1). In addition, the undetermined parameters only represent the marginal utility of each variable.

As the car traffic increases continuously, it has become the main source of traffic volume. Therefore, this paper studies the mean utility of the road for cars. In addition, the road is divided by toll stations, and the travel time is far beyond the delay at the toll stations. Therefore, the delay at toll stations is not taken into consideration in travel time in this study.

3.2. The Improved Comprehensive Mean Utility of Users of PPP Highway Projects. It can be observed that there is a one-to-one correspondence between the parameters T_i, C_i, and A_i in formula (1) and risk categories (travel time, willingness to pay, and comfort level) in Table 2. Therefore, risk coefficients were introduced to quantify relevant risks based on the mean utility formula and the actual traffic situation. Consequently, the comprehensive mean utility function was constructed to predict actual practices.

3.2.1. Travel Time Risk Coefficient: The Time Cost Coefficient a_{i1}. Road traffic time = highway length/average speed; average speed is calculated with speed-flow general model under any traffic load (formula (2)) [27]:

$$\left.\begin{aligned} U &= \frac{\alpha_1 \cdot U_s}{1 + (V/C)^{\beta}} \\ \beta &= \alpha_2 + \alpha_3 (V/C)^3 \end{aligned}\right\}, \tag{2}$$

U is the average speed under the corresponding traffic load (km/h); U_s is the design speed of the corresponding road level (km/h); V is the traffic volume; C is the highway capacity; V/C is the traffic load of the corresponding road level; α_1, α_2, and α_3 are regression parameters; for highway, $\alpha_1 = 0.93$, $\alpha_2 = 1.89$, and $\alpha_3 = 4.86$ [23].

The traffic time is objective and can be calculated by formula (2). It mainly depends on factors such as the design speed, traffic volume, and road traffic capacity. In real life, however, users' satisfaction to the road conditions will change the length of the actual time which we call it psychological time. In other words, psychological time is a mixture of the objective time and the satisfaction of users. The time cost coefficient a_{i1} was introduced into the model to quantify the influence of serious congestion and poor road conditions upon psychological time cost. It is the ratio of psychological time and the objective travel time. The psychological time would be greater than the actual time in the event of road construction, insufficient road maintenance, and traffic growth. The value of the coefficient will increase in the future.

3.2.2. Travel Cost Risk Coefficients: Charging Impedance Coefficient a_{i2} and Fuel Consumption Coefficient a_{i3}. This paper introduced charging impedance coefficient a_{i2} and fuel consumption coefficient a_{i3} to analyze the travel cost.

(1) Charging Impedance Coefficient a_{i2}. The actual tolls of the PPP highway are determined by toll rates and road length. According to the case analysis in Table 1, high tolls and long charging period will draw public opposition. This model introduced the charging impedance coefficient a_{i2} to quantify the users' willingness to pay. It is the ratio of psychological cost and actual cost. Initially, users cannot adjust to the charging system. Thus, the public will strongly oppose to it and the coefficient value is very high. As the users gradually accept the charging system, the coefficient will reduce gradually. However, the coefficient would increase again if experiencing driving comfort reduction and social and economic disruption. In addition, economic risk factors such as high tolls and long toll collecting period are closely related to the users' ability to pay. Thus, the coefficient also depends on the users' income level. Therefore, the influential factors of charging impedance coefficient are income level, years of use, road condition, and congestion condition.

(2) Fuel Consumption Coefficient a_{i3}. This paper conducted regression simulation of 93# gasoline price over 10 years. The initial value of gasoline price is set at 1.527 yuan/L, and price inflation is 0.3487 in the simulation. As the road condition and other factors affect the actual fuel consumption, fuel consumption coefficient a_{i3} was introduced into this model to more truly reflect the car's fuel consumption, which is the ratio of actual fuel consumption and objective fuel consumption.

3.2.3. Comfort Coefficient γ_i. This paper introduced the comfort coefficient γ_i to quantify the comfort level perceived by the users. The comfort level also directly affects the psychological travel time. When the comfort level is lower, the travel time feels longer to the users. On the contrary, when the traffic is unobstructed and the road condition is good, the travel time feels shorter, and the comfort level and the coefficient value are higher.

3.2.4. Time Value of Cars v_t. Time value of cars is defined as the monetary value of the opportunity cost of the time which users consumed on the trip. The travel cost can be converted into generalized travel time via time value of cars. According to literature, the time value of private car drivers should be between 27.82 and 29.17 yuan/hour [28, 29]. Considering the inflation, the lack of historical data and many other factors, this paper set the average car time value as 22 yuan/hour.

Compared to formula (1), this paper combined the travel time with the comfort coefficient to doubly strengthen the users' consumption psychology. The psychological travel time is represented by the product of the ratio of the computed travel time t_i and comfort coefficient γ_i and time cost coefficient a_{i1}. Similarly, the travel cost is divided into two parts of the tolls and fuel consumption. The public willingness to pay and the actual fuel consumption are represented by the charging impedance coefficient a_{i2} and fuel consumption coefficient a_{i3}. To unify the measuring units, the time value of cars v_t was introduced to convert the travel cost into generalized travel time. The mean utility of PPP highways is represented by psychological travel time and the converted generalized travel time by using the following equation:

$$M_i = a_{i1} \cdot \frac{t_i}{\gamma_i} + \left(a_{i2} \cdot r_i + a_{i3} \cdot p_e\right) \cdot \frac{l_i}{v_t}, \tag{3}$$

a_{i1} is the time cost coefficient of the road i, t_i is the travel time of the road i, γ_i is the comfort coefficient of the road i, a_{i2} is the charging impedance coefficient of the road i, r_i is the toll rate, a_{i3} is the fuel consumption coefficient of the road i, p_e is the price of petrol, l_i is the length of the road i, and v_t is the time value of cars.

3.3. The Traffic Allocation Model. The MNL model of choice probabilities based on mean utility of users is used to calculate the simulated traffic allocation rate using the following equation:

$$\begin{cases} P_i = \exp\dfrac{(-\sigma M_i/M)}{\sum_k \exp(-\sigma M_k/M)}, \\ M_i = \dfrac{a_{i1} t_i}{\gamma_i} + (a_{i2} r_i + a_{i3} p_e)\dfrac{l_i}{v_t}, \end{cases} \tag{4}$$

P_i is the probability of users selecting road i, M_i is the mean utility of the road i, M is the average of mean utility of k roads, and σ is the distribution parameter, and $\sigma = 3.00$ [23].

4. The Regression Equations of Main Risk Coefficients

4.1. Questionnaire Survey. This paper selects the multivariate linear regression method to quantify the risk factors in formula (3). The factors affecting those risks are surveyed using a questionnaire. The questionnaire consists of two parts: the demographic information of respondents and main questions. Demographic information covers gender, driving experience, and monthly income. Main questions are related to psychological time, willingness to pay, and comfort. Respondents are required to answer the questions based on their feelings of overall highway driving experiences. The target respondents were car drivers. In total, 38 questionnaires were sent out, and 37 valid questionnaires were received with a response rate of 95%. Over 70% of respondents are male, and about 75% of respondents have a driving experience of more than five years. The number of required samples for the multiple linear regression method should be 3 to 10 times more than the influencing factors. As reported in the previous section, there are 4 influence factors in this study: road condition, congestion condition, income level, and years of driving. A collection of 37 effective responses make it qualified for the regression analysis.

4.2. Multiple Linear Regression Analysis. In this study, the time cost coefficient, charging impedance coefficient, and comfort coefficient were included in the regression analysis. The independent variables and dependent variables of multiple linear regression are shown in Table 3. The scoring of the variables is shown in Table 4. After organizing the survey data, regression analysis was conducted via SPSS. The results are shown in Table 5 and 7.

As shown in Table 5, R^2 values are high, 0.877, 0.867, and 0.963 for three coefficients, respectively, which indicates a good fit of the regression model. Table 6 shows that the probability P values are all less than the significance level of 0.05, indicating a strong sign of the significant linear relationship between independent variables and dependent variables. Table 7 shows the values of constant terms and the partial correlation coefficients of independent variables of the regression model. Their probability P values are also less than the significance level of 0.05. The regression equation of each risk factor could be achieved (formula (5)). The risk coefficient values can be determined based on formula (5).

In the practical application, each independent variable value should be within the value range (i.e., minimum and maximum values) in Table 4. If the values of road condition, congestion condition, and income levels are all 5 and the value of years of use is 10, the values of the time cost coefficient and the charging impedance coefficient will be 0.35 and 0.32, respectively, which are minimum values. The comfort coefficient value is 1.68 which is the maximum value. When the value of road condition, congestion condition, income levels, and years of use are all 1, the values of the time cost coefficient and the charging impedance coefficient are 1.72 and 1.68, respectively, which are maximum values. The comfort coefficient value is 0.28 which is the minimum value. Therefore, the value range of the time cost coefficient is (0.35, 1.72). When the time-cost coefficient value is 1, the actual travel time is consistent with the psychological feeling time. When the actual time is gradually greater than the psychological time, the value of the time cost coefficient will be gradually greater than 1. On the contrary, it might be gradually less than 1. The value range of charging impedance coefficient is (0.32, 1.68). When the charging impedance coefficient value is 1, the users can just accept the charging system. The lower the users' willingness to pay is, the greater the charging impedance coefficient value is. On the contrary, it may become smaller gradually. The value range of the comfort coefficient is (0.28, 1.68). The higher the comfort level is, the higher the coefficient value is. On the contrary, it may become lower gradually:

$$\begin{cases} a_{i1} = 2.059 - 0.173 \times d_1 - 0.169 \times d_2, \\ a_{i2} = 1.955 - 0.109 \times d_1 - 0.065 \times d_2 - 0.056 \times s_1 - 0.049 \times s_2, \\ \gamma_i = 0.171 \times d_1 + 0.180 \times d_2 - 0.076, \end{cases} \tag{5}$$

a_{i1} is the time cost coefficient, a_{i2} is the charging impedance coefficient, γ_i is the comfort coefficient, d_1 is the road condition value, d_2 is the congestion condition value, s_1 is the income level, and s_2 denotes the years of use.

5. Case Study: System Dynamics Model Simulation Analysis

5.1. Background. The highway network selected in this paper includes four highways: Xicheng highway, Shanghai-Nanjing highway, Changzhou-Hefei highway, and Nantong-Wuxi highway which form the square network structure (Figure 1). Xicheng highway was opened to public in 1999. It has six lanes in both directions. The length of the selected section is about 24 km. Shanghai-Nanjing highway was opened to travel in 1996. It has eight lanes in both directions after reconstruction. The length of the selected section is about 25 km. Changzhou-Hefei highway was opened to travel in 2004. It has four lanes in both directions. The length of the selected section is about 25 km. Nantong-Wuxi highway was opened to travel in 2010. It has six lanes in both directions. The length of the selected section is about 28 km. They were all invested by the Traffic Financing and Investment Company of Govenment and built under the

Table 3: Independent variables and dependent variables of multiple linear regression.

The dependent variables	The independent variables
Time cost coefficient	Road condition and congestion condition
Charging impedance coefficient	Road condition, congestion condition, income level, and years of use
Comfort coefficient	Road condition and congestion condition

Table 4: Scoring of variables.

Number	The variable name	Definition
1	Road condition	5: very good; 4: good; 3: neutral; 2: poorer; 1: very poor
2	Congestion condition	5: very mild; 4: mild; 3: neutral; 2: serious; 1: very serious
3	Income level	5: above 8000 yuan; 4: 6000–8000 yuan; 3: 4000–6000 yuan; 2: 2000–4000 yuan; 1: below 2000 yuan
4	Years of use	2: 1-2 years; 4: 3-4 years; 6: 5-6 years; 8: 7-8 years; 10: 9-10 years
5	Deteriorating degree	0.5: very serious; 0.4: serious; 0.3: neutral; 0.2: mild; 0.1: very mild
6	Time cost coefficient (corresponding to the psychological time)	1.5: very long; 1.2: longer; 1: neutral; 0.8: short; 0.5: very short
7	Charging impedance coefficient (corresponding to willingness to pay)	1.5: very low; 1.2: lower; 1: neutral; 0.8: higher; 0.5: very high
8	Comfort coefficient (corresponding to the overall comfort)	1.5: very comfortable; 1.2: more comfortable; 1: neutral; 0.8: not too comfortable; 0.5: very uncomfortable

Table 5: Model summary.

The dependent variable	R	R^2	Adjusted R^2	The standard estimate error
Time cost coefficient	0.937[a]	0.877	0.870	0.0909
	[a]Prediction variables: (constant), congestion condition, and road condition.			
Charging impedance coefficient	0.931[a]	0.867	0.851	0.0946
	[a]Prediction variables: (constant), road condition, congestion condition, income level, and years of use			
Comfort coefficient	0.981[a]	0.963	0.961	0.0493
	[a]Prediction variables: (constant), congestion condition, and road condition.			

Table 6: Variance analysis.

Model		Sum of squares	df	Mean square	F	Significance
Time cost coefficient	Regression	2.006	2	1.003	121.489	0.000[a]
	Residual	0.281	34	0.008	—	—
	Totals	2.287	36	—	—	—
	[a]Prediction variables: (constant), congestion condition, and road condition.					
Charging impedance coefficient	Regression	1.871	4	0.468	52.276	0.000[a]
	Residual	0.286	32	0.009	—	—
	Totals	2.157	36	—	—	—
	[a]Prediction variables: (constant), road condition, congestion condition, income level, and years of use					
Comfort coefficient	Regression	2.150	2	1.075	442.249	0.000[a]
	Residual	0.083	34	0.002	—	—
	Totals	2.233	36	—	—	—
	[a]Prediction variables: (constant), congestion condition, and road condition.					

Table 7: Regression coefficient.

The dependent variable	The independent variables	Unstandardized coefficients		Standardized coefficients	t	Siginificance
		B	Standard error	Trial version		
Time cost coefficient	(Constant)	2.059	0.068	—	30.356	0.000
	Road condition	−0.173	0.016	−0.639	−10.564	0.000
	Congestion condition	−0.169	0.013	−0.759	−12.560	0.000
Charging impedance coefficient	(Constant)	1.955	0.082	—	23.888	0.000
	Road condition	−0.109	0.020	−0.413	−5.322	0.000
	Congestion condition	−0.065	0.015	−0.302	−4.230	0.000
	Income level	−0.056	0.016	−0.251	−3.446	0.002
	Years of use	−0.049	0.010	−0.430	−5.031	0.000
Comfort coefficient	(Constant)	−0.076	0.037	—	−2.071	0.046
	Road condition	0.171	0.009	0.636	19.154	0.000
	Congestion condition	0.180	0.007	0.821	24.729	0.000

scheme "returning loan by collecting tolls." It is similar with the PPP highway projects which need to charge users the tolls within a certain period to repay the loan. Therefore, they are selected for case study.

Jiangsu Expressway Company Limited is a listed company owning all or part of the rights and interests of the tolled bridges and highways in Jiangsu Province such as Shanghai-Nanjing highway, Xicheng highway, and Guangzhou-Jingling highway. Its operation data can be accessed and can serve as the simulated data source. The rest traffic volume data of the highways are all from the local-related departments. Therefore, the simulated data source is reliable enough to establish the system dynamic model. After passing the reliability test, the model can be used to forecast the future traffic volume which can provide the scientific basis for adjusting the key contract conditions or other applications. The simulation took Node A as a starting point and Node D as a finishing point to simplify the simulation process. This paper only took the converted annual traffic between point A and D as the simulation basis. Because Nantong-Wuxi highway opened to traffic in 2010, this paper verifies the reliability of the traffic allocation model by fitting highway traffic from 2011 to 2016.

Figure 1: The sketch of network of the case highway.

5.2. System Dynamics Model of Traffic Allocation Rate of PPP Highway. Based on formula (4), the relevant theories, and modeling of traffic allocation, three state variables were selected as the total traffic, AB section traffic, and AC section traffic. The corresponding rates were the traffic growth rates of each variables, respectively. The mean utility of sections could be calculated by formulas (2) and (3). Afterwards, traffic allocation rate and traffic volume will be determined according to the MNL model (formula (4)). The traffic volume of the specific year and previous year decided the traffic growth rate of sections. A complete feedback loop of traffic distribution was established. The stock and flow model of the PPP highway mean utility is shown in Figure 2.

5.3. The Main Vensim Equations for the Road Mean Utility. To simulate the traffic volume of a road, the quantitative relationship between variables which are called Vensim equation and the related data from real projects should be input into the stock and flow model which we call normal system dynamic model of system dynamics (Figure 3) [30]. According to formula (3), the mean utility (Mi) in the system dynamics model is described as follows:

M_i = time cost coefficient a_{i1} ∗ section travel time SECTRTIME/comfort coefficient γ_i + (charging impedance coefficient a_{i2} ∗ section toll SECTOLL + fuel consumption coefficient a_{i3} ∗ the petrol price of cars per a hundred kilometers CARPPRI) ∗ section length SECLEG/the car time value CARTVLUE

This comprehensive mean utility function consists of two parts: travel time and tolls. Risk factors related to time, tolls, and comfort level were measured quantitatively to the time-cost coefficient a_{i1}, comfort coefficient γ_i, charging impedance coefficient a_{i2}, etc. by using formula (5). Based on formula (4) and the highway conditions, the traffic allocation rate of the various highways of the calendar year could be

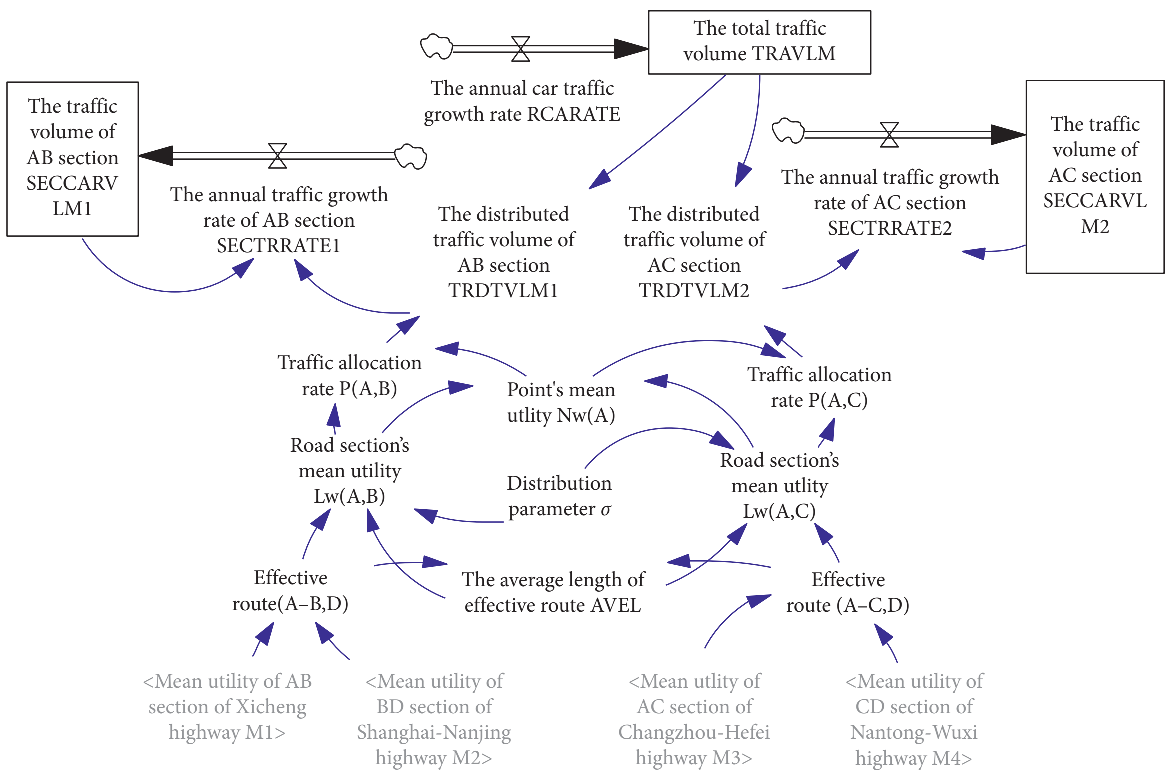

Figure 2: The stock and flow model of traffic allocation.

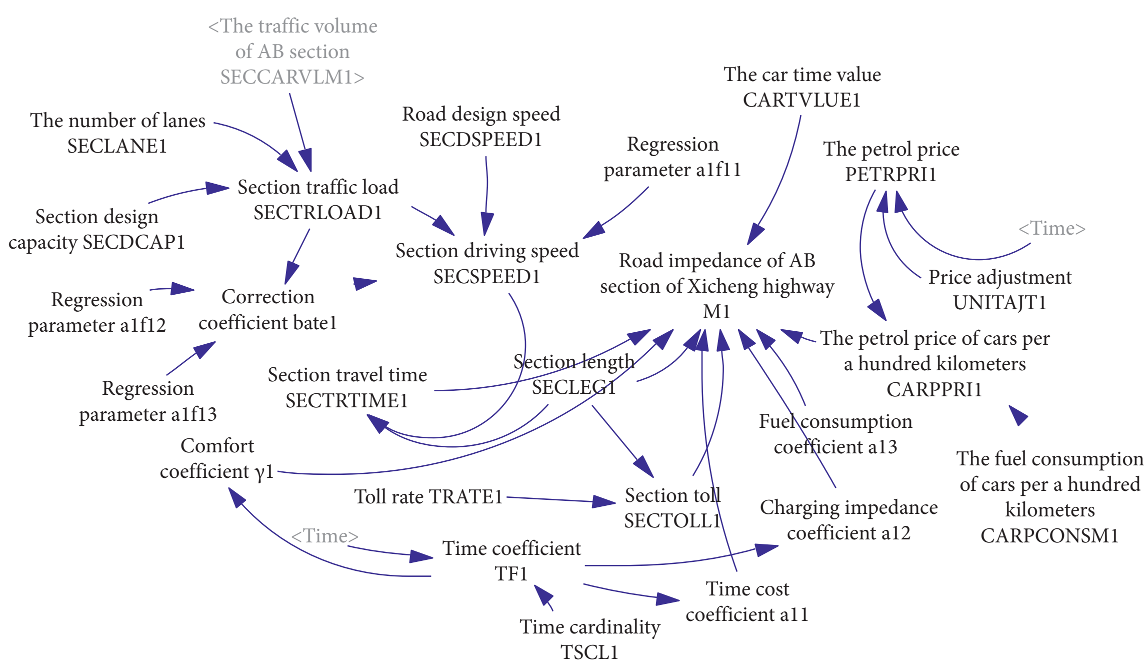

Figure 3: The normal system dynamic model of Xicheng highway.

computed by running the normal system dynamic model of Xicheng highway.

To determine the value of risk coefficients, a survey was conducted to determine the road condition and congestion level of the case roads, the survey shows the average deterioration value of current road conditions year-by-year was 0.21, and the current congestion condition year-by-year was 0.3. According to the operating conditions, Nantong-Wuxi highway was opened to traffic in 2010. As a result, its initial value of road and congestion conditions was set as 5. The initial value of road and congestion conditions of Changzhou-Hefei highway was set as 4. Xicheng and

Table 8: The Vensim equation and valuation of road impedance of every highway.

Number	The parameter name	Vensim equation	Valuation			
			Xicheng highway	Shanghai-Nanjing highway	Changzhou-Hefei highway	Nantong-Wuxi highway
1	Section travel time	**SECTRTIME** = SECLEG/ SECSPEED.K SECSPEED = alfi1 * SECDSPEED.K/(1 + SECTRLOAD.K^ betai)	SECLEG1 = 24 SECDSPEED1 = 120	SECLEG2 = 25 SECDSPEED2 = 120	SECLEG3 = 25 SECDSPEED3 = 120	SECLEG4 = 28 SECDSPEED4 = 120
2	Section toll	**SECTOLL** = SECLEG * TRATE	TRATE1 = 0.45	TRATE2 = 0.45	TRATE3 =0.60	TRATE4 = 0.55
3	The petrol price of cars per hundred kilometers	**CARPPRI** = PETRPRI * CARPCONSM	PETRPRI = 1.527 + Time * 0.3487CARPCONSM = 8.5/100	—	—	—
4	The car time value	**CARTVLUE**	22	—	—	—
5	Time cost coefficient	**ai1.K** = TABLE (Tai1, TFi.K, 0, 1, 0.1)	Ta11 = 1.03/1.12/1.21/ 1.30/1.39/1.48/1.57/ 1.63/1.66/1.70 If TIME ≤ 10, TF1 = TIME/10, Else TF1 = 1	Ta21 = 1.38/1.46/1.55/1.64 /1.69/1.72/1.72/1.72/ 1.72/1.72 If TIME ≤ 10, TF2 = TIME/10, Else TF2 = 1	Ta31 = 0.69/0.78/0.87/ 0.96/1.05/1.13/1.22/1.31/ 1.40/1.49 If TIME ≤ 10, TF3 = TIME/10, Else TF3 = 1	Ta41 = 0.35/0.44/0.53/ 0.62/0.70/0.79/0.88/ 0.97/1.06/1.15 If TIME ≤ 10, TF4 = TIME/10, Else TF4 = 1
6	Comfort coefficient	**γi.K** = TABLE (Tgamai, TFi.K, 0, 1, 0.1)	Tγ1 = 0.98/0.89/0.79/0.70/ 0.61/0.52/0.43/0.37/0.33/0.29 If TIME ≤ 10, TF1 = TIME/10, Else TF1 = 1	Tγ2 = 0.63/0.53/0.44/0.35/ 0.30/0.28/0.28/0.28/0.28/ 0.28 If TIME ≤ 10, TF2 = TIME/10, Else TF2 = 1	Tγ3 = 1.33/1.24/1.14/ 1.05/0.96/0.87/0.78/0.69/ 0.59/0.50 If TIME ≤ 10, TF3 = TIME/10, Else TF3 = 1	Tγ4 = 1.68/1.59/1.50/1.40/ 1.31/1.22/1.13/1.04/ 0.95/0.85 If TIME ≤ 10, TF4 = TIME/10, Else TF4 = 1
7	Charging impedance coefficient	**ai2.K** = TABLE (Tai2, TFi.K, 0, 1, 0.1)	Ta12 = 1.27/1.25/1.24/1.22/1.20/ 1.17/1.15/1.12/1.09/1.06 If TIME ≤ 10, TF1 = TIME/10, Else TF1 = 1	Ta22 = 1.45/1.43/1.41/1.39/1.35/ 1.31//1.24/1.17/1.10/1.02If TIME ≤ 10, TF2 = TIME/10, Else TF2 = 1	Ta32 = 1.10/1.08/1.06/1.04/ 1.02/1.00/0.97/0.95/0.92/0.89 If TIME ≤ 10, TF3 = TIME/10, Else TF3 = 1	Ta42 = 0.92/0.91/0.89/0.87/ 0.85/0.82/0.80/0.77/0.75/0.72 If TIME ≤ 10, TF4 = TIME/10, Else TF4 = 1
8	Fuel consumption coefficient	**ai3**	0.9	0.9	0.8	0.8

Table 9: The actual and simulated allocation of Xicheng expressway from 2011 to 2016.

Year	The actual traffic of Xicheng highway (ten thousand vehicles/year) (2)	The SD simulated traffic of Xicheng highway (ten thousand vehicles/year) (3)	The average error rate between SD simulated traffic and actual traffic ((3)−(2))/(2)
2011	402.65	376.54	−6.49%
2012	435.81	410.07	−5.91%
2013	456.93	440.46	−3.60%
2014	478.67	470.91	−1.62%
2015	490.58	503.65	2.67%
2016	511.81	536.31	4.79%
The average error rate			−1.69%
The average absolute value of the error rate			4.18%

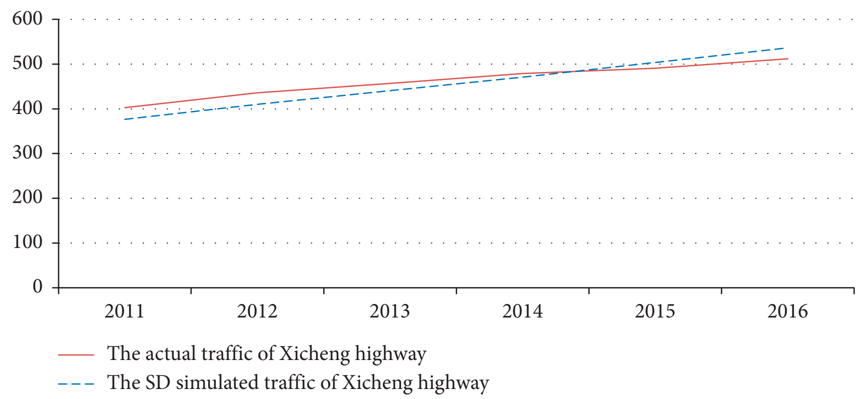

Figure 4: The comparison of the actual and simulated traffic volume of Xicheng Expressway.

Shanghai-Nanjing highway was opened to public earlier, and their traffic was higher. Shanghai-Nanjing highway was opened to public at the earliest date. Therefore, the initial value of road and congestion conditions of Xicheng highway was set as 3. The initial value of road and congestion conditions of Shanghai-Nanjing highway was set as 2. In addition, the survey result showed that the average monthly income level of the private car owners was 3.24 (more than 6000 yuan). The average monthly income of the rest years could be pushed back according to per capita disposable income growth rate of 10.1% from National Bureau of Statistics of China. The values of main risk coefficients of each highway from 2011 to 2016 could be calculated based on formula (5). In addition, due to the heavy traffic of Xicheng and Shanghai-Nanjing highway, their driving distractions was bigger. Their fuel consumption of cars was slightly higher than the rest two highways. But because the highways are totally enclosed and the driving speed is uniform, their fuel consumption coefficient value was set as 0.9. The fuel consumption coefficient value of Changzhou-Hefei and Nantong-Wuxi highway was set as 0.8.

The values of the rest parameters of each highway were derived from the objective data. The Vensim equations of the parameters and the valuation are shown in Table 8.

5.4. Simulation Analysis of System Dynamics Specification Model of Xicheng Highway. The SD model of mean utility and traffic allocation model is used to simulate the traffic of Xicheng highway from 2011 to 2016 (Jiangsu Expressway Company Limited) [31]. The simulation results are shown in Table 9 and Figure 4. The average error rate between actual traffic volume and SD simulated one of Xicheng highway is 1.69%. The average absolute value of the error rate is 4.18%. The error rate is very low. The model has accurately described the traffic volume changing trend of the case highway.

6. Conclusions

This paper studies the operation effectiveness of PPP highways. First, recent problematic PPP highway projects were deeply analyzed to identify the main risk factors related to traffic volume. Based on users' subjective feelings, risk coefficients were introduced to quantify relevant risks. The PPP highway traffic allocation model considering the effect of risks was established. The risk effects are statistically computed using multiple linear regression analysis via SPSS. One PPP highway project was simulated to validate the proposed traffic allocation model by comparing the actual traffic volume of the road with the simulated one. The simulation results show that the traffic allocation model can improve the accuracy of the traffic forecasting.

Data Availability

The data in the paper were received through the questionnaire survey, and the data in terms of the case were obtained from the website available publicly (http://www.jsexpressway.com/index.php?m=trafficflow&c=index&catid=113&cid=126,152).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

A New Approach to Studying Net Present Value and the Internal Rate of Return of Engineering Projects under Uncertainty with Three-Dimensional Graphs

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Cost-benefit analysis (CBA) is very useful when appraising engineering projects and examining their long-term financial and social sustainability. However, the inherent uncertainty in the estimation of completion time, final costs, and the realization of benefits often act as an impediment to its application. Since the emergence of fuzzy set theory, there have been significant developments in uncertainty modelling in project evaluation and investment analysis, primarily in the area of formulating a fuzzy version of CBA. In this context, in studying the key indicators of CBA, whereas fuzzy net present value (fNPV) has been investigated quite extensively, there are significant issues in the calculation of fuzzy internal rate of return (fIRR) that have not been addressed. Hence, this paper presents a new conceptual model for studying and calculating fNPV and fIRR. Three-dimensional fNPV and fIRR graphs are introduced as a means of visualizing uncertainty. A new approach is presented for the precise calculation of fIRR. To facilitate practical application, a computerization process is also presented. Additionally, the proposed methodology is exemplified in a sample motorway project whereby its advantages over traditional stochastic uncertainty modelling techniques such as Monte Carlo analysis are discussed. Overall, it is concluded that the new approach is very promising for modelling uncertainty during project evaluation for both project managers and project stakeholders.

1. Introduction

Cost-benefit analysis (CBA) is a valuable decision support tool in project evaluation in both the public and private sectors [1]. It is widely acknowledged that the fundamental principles of CBA are accredited to the work of the French civil engineer and economist Jules Dupuit in the 1840s [2]. After being used systematically in the U.S. in the 1930s, by the end of the 1960s, the use of CBA spread around the world in both developed and developing countries [3]. Its broad purpose is to help decision-making and to make it more rational by the more efficient allocation of available resources [4]. Today, many international financial institutions and international organisations such as the European Investment Bank use CBA to appraise the economic desirability of projects [5].

Reasonably, the fundamental difficulties in the estimation of completion time, final costs, and the realization of benefits often act as an impediment to the application of CBA. Hence, besides its significance and importance, there are limitations to its application because of the underlying approximations, the working hypotheses, and the possible lack of data [6]. Additionally, Belli and Guerrero [7] conclude that when CBA project documents are assessed, risk analysis emerges as one of the weakest areas. Since uncertainty management in CBA is identified as problematic, research is needed to improve existing techniques. It is envisaged that innovations and improvements can increase its importance in engineering decision-making theory and practice.

The primary indicators in CBA are the net present value (NPV) which is expressed in monetary values and the internal rate of return (IRR) [3]. The purpose of this paper is to present an uncertainty management model that applies fuzzy set theory to these indicators. Also, an automation process based on computer processing is presented to facilitate application. Last but not least, a case study is discussed to exemplify both the application of the approach presented in this paper and the introduction of uncertainty due to decisions made during the design and planning phases of an engineering project. Finally, the overall conclusions of this work are presented.

2. Literature Review

2.1. Stochastic and Fuzzy Risk Assessment in CBA. Stochastic risk assessment, in CBA, can be performed primarily with Monte Carlo risk analysis, which is a sophisticated technique that starts by specifying stochastic probability distributions for significant uncertain quantitative assumptions. After that, a trial is taken by taking a random draw from the distribution of each parameter. This step is repeated several times in order to produce a histogram that depicts the realization of net benefits. The underlying assumption is that as the number of trials increases, the frequencies will converge towards the true underlying probabilities [4].

There has been extensive research in applying fuzzy set theory in CBA. Kaufmann and Gupta [8] discussed the discounting problem with fuzzy discounting rates and crisp (nonfuzzy) investment costs. Wang and Liang [9] proposed two algorithms to conduct CBA in a fuzzy environment in which it is difficult to obtain exact assessment data such as investment benefit, expenses, project lifetime, gross income, expenses, and depreciation. Mohamed and McCowan [10] proposed a method for modelling the effects of both monetary (construction cost and annual revenue) and nonmonetary (political, environmental, organizational, competition, and market share) aspects of investment options with possibility theory. Schjaer-Jacobsen [11] set out to examine the possibility of attaining a reasonably useful and realistic picture of the economic consequences of strategic decisions when little is known about the future. He argued that the quality of available information to decision-makers renders traditional decision theory and investment calculations obsolete, while he also demonstrated the representation of economic uncertainties in an investment example with the aid of triangular fuzzy numbers. Dompere [12] studied the discounting process under uncertainty and examined the theory of the fuzzy present value. Chiu and Park [13] developed a fuzzy cash flow analysis for engineering decisions. Sorenson and Lavelle [14] compared fuzzy set and probabilistic paradigms for ranking vague economic investment's information and concluded that cash flows and interest rates should be modelled by fuzzy sets and ranked with a fuzzy ranking method. Sewastjanow and Dymowa [15] recognized how the obtaining of fuzzy IRR is a rather open problem and to this extent examined a framework for solving fuzzy equations. Tsao [16] presented a series of algorithms to calculate fuzzy net present values of capital investments in an environment with uncertainty. He suggested that the imprecision and uncertainty of the project cash flow are higher than that of the cost of capital.

Beyond the development of a fuzzy version of CBA, there is significant research in applying fuzzy set theory in uncertainty in variables that regard the costs and the cash flow of projects. Kishk [17] applied fuzzy set theory in a whole life costing modelling. Shaheen et al. [18] presented a methodology for extracting fuzzy numbers from experts and processing the information in fuzzy range cost estimation analysis. More so, fuzzy project scheduling (FPS) is based on the application fuzzy set theory in traditional scheduling techniques and is useful in dealing with circumstances involving uncertainty, imprecision, vagueness, and incomplete data [19]. The critical concept is modelling activity duration and cost with fuzzy numbers and thereby calculating project duration and cost, activity start and finish dates, and activity criticality. As such, Maravas and Pantouvakis [20] have shown how fuzzy cost estimates of project activities can be combined with fuzzy project scheduling to yield project cash flow projections.

Regarding project benefits, in the specific case of transportation projects, fuzzy traffic assignment models indicate the region of the expected project benefits. Teodorovic [21] emphasized the importance of fuzzy logic systems as universal approximators in solving traffic and transportation problems. Henn and Ottomanelli [22] applied possibility theory in traffic assignment modelling. Ghatee and Hashemi [23] proposed a traffic assignment model with a fuzzy level of demand. Triangular fuzzy numbers were used to show the imprecise number of travellers who want to travel between origin-destination pairs. Caggiani et al. [24] used fuzzy programming to improve origin-destination matrix estimation based on traffic counts and other uncertain data. De Ona et al. [25] used fuzzy optimization to obtain adjusted values of field traffic volume data to meet consistency constraints.

While the NPV and IRR are the most widespread and accepted indicators when conducting CBA analysis, there are significant developments in the study of IRR. As such, Magni [26] introduced the concept of the average internal rate of return (AIRR) as an alternative to the well-established IRR. While dismissing the IRR equation, he argued about the superiority of the AIRR. Guerra et al. [27] applied fuzzy set theory to the AIRR to study investment appraisal under uncertainty. Jiang [28] presented a particular case of a continuous AIRR, named excess return of time-scaled contributions (ERTC) that can be used in capital budgeting and project finance. Mørch et al. [29] considered the maximization of the AIRR in the renewal of maritime shipping capacity.

Overall, besides the significant research in applying fuzzy set theory to CBA, there are significant issues that need to be researched—primarily, the study of the variation of fuzzy NPV in regard to the discount rate and the calculation of fuzzy IRR. Additionally, the emergence of new fuzzy techniques in cost estimations, cash flow prediction, and benefit analysis provides an opportunity for formulating fuzzy variables that can thereafter be used as base estimates in a holistic risk assessment methodology. Finally, the newly introduced AIRR and its fuzzy equivalent could potentially be adopted in CBA analysis.

2.2. Fundamentals of Fuzzy Set Theory. Fuzzy Set Theory is used to describe and quantify uncertainty and imprecision in data and functional relationships. A fuzzy subset A of a universe of discourse U is characterized by a membership function μ_A: U $\rightarrow$ [0, 1] which associates with each element x of U a number $\mu_A(x)$ in the interval [0, 1] which represents the grade of membership of x in A. In fuzzy set theory, the triangular membership function which is defined by three numbers a, b, and c is encountered very often. Hence, a triangular fuzzy number $\tilde{x} = \langle a, b, c \rangle$ has the following membership function:

$$\mu_A(x) = \begin{cases} 0, & x < a, \\ \dfrac{(x-a)}{(b-a)}, & a \le x \le b, \\ \dfrac{(c-x)}{(c-b)}, & b \le x \le c, \\ 0, & x > c. \end{cases} \quad (1)$$

Every fuzzy set A can be associated to a collection of crisp sets known as α-cuts (alpha-cuts) or α-level sets. An α-cut is a crisp set consisting of elements of A which belong to the fuzzy set at least to a degree of α. As such, if A is a subset of a universe U, then an α-level set of A is a nonfuzzy set denoted by A_α which comprises all elements of U whose grade membership in A is greater than or equal to α [30]. In symbols,

$$A_\alpha = \{u \mid \mu_A(u) \ge \alpha\}, \quad (2)$$

where α is a parameter in the range $0 < \alpha \le 1$.

Effectively, an α-cut is a means to defuzzify a fuzzy set into a crisp set at desired α-levels which reflect the perceived risk. More specifically, every α-cut indicates the pessimistic and optimistic values for the same risk level, and in the case of a triangular fuzzy number, it is given by the following formula:

$$A_\alpha = [\alpha(b-a) + a,\ \alpha(b-c) + c]. \quad (3)$$

In many cases, it is necessary to compare fuzzy numbers in order to attain a linear ordering. In such cases, the removal number can be defined as the first criterion for the linear ordering. Essentially, it is an ordinary representative of the fuzzy number; in the case of a triangular fuzzy number, it is given by the following formula [8]:

$$u = \frac{1}{4(a + 2b + c)}. \quad (4)$$

The second criterion is the mode of the fuzzy number, that is, "b" for the triangular fuzzy number $\tilde{x} = \langle a, b, c \rangle$. Finally, the divergence of the fuzzy number around the mode is the third criterion. It is given by the following formula:

$$\mathrm{div}_x = c - a. \quad (5)$$

3. Fuzzy NPV and IRR

3.1. Three-Dimensional Graphical Representation of Fuzzy NPV and IRR. The net present value (NPV) is essentially the discounted net cash flow—the sum that results when the discounted expected financial costs of investment are subtracted from the discounted value of the expected benefits:

$$\mathrm{NPV} = C_0 + \frac{C_1}{1+i} + \frac{C_2}{(1+i)^2} + \cdots + \frac{C_n}{(1+i)^n}, \quad (6)$$

where i is the crisp financial discount rate and C_n is the crisp net cash flow at period n.

However, in the presence of uncertainty, all values may be modelled with fuzzy numbers. Hence, the fuzzy-net present value (fNPV) is defined as follows [31]:

$$\mathrm{fNPV} = \tilde{C}_0 + \frac{\tilde{C}_1}{1+\tilde{i}} + \frac{\tilde{C}_2}{(1+\tilde{i})^2} + \cdots + \frac{\tilde{C}_n}{(1+\tilde{i})^n}, \quad (7)$$

where $\tilde{i}$ is the fuzzy financial discount rate and $\tilde{C}_n$ is the fuzzy net cash flow at period n.

The crisp internal rate of return (IRR) is defined as the discount rate for which the net present value is equal to zero. In essence, it is the discount rate for which the costs are equal to the benefits. It is a measure of the profitability and the final yield of the investment. Thus, in practice, a project is more desirable if it has a higher value of IRR. However, the IRR cannot be calculated analytically from Equation (6). To this extent, numerical methods are employed to find an acceptable value based on convergence criteria. Since the fuzzy net present value (fNPV) is a fuzzy variable, the fuzzy internal rate of return (fIRR) is expected to be a set of discount rates for which fNPV is equal to zero instead of a single number. Hence, the calculation of this fIRR poses a significant challenge.

To this purpose, it is proposed that Cartesian geometry and a three-dimensional Euclidean space are used to graph fNPV and calculate fIRR. Thus, uncertainty can be represented by a three-dimensional plot in which the x axis represents the discount rate, the y axis the NPV, and the z axis the value of possibility [32]. In effect, these plots give the ability to scan across various discount rates and show the membership functions of fNPV for every such value (Figure 1). The plots can show the change in the uncertainty of fNPV in regard to the value of the discount rate. Thus, examining the slope of this plot and the change of the width of individual fNPV shows the variation of uncertainty in the project.

Besides, gaining insights into fNPV, three-dimensional graphs provide a novel manner for defining and calculating fIRR. Hence, the fuzzy internal rate of return (fIRR) is the set that is defined by the intersection of the xz plane (x and z axes at $y = 0$) with the fuzzy net present value (fNPV) for various values of the discount rate:

$$\mu_{\mathrm{fIRR}} = P_{xz} \cap \mu_{\underset{i=0}{\overset{R}{\mathrm{fNPV}}}}, \quad (8)$$

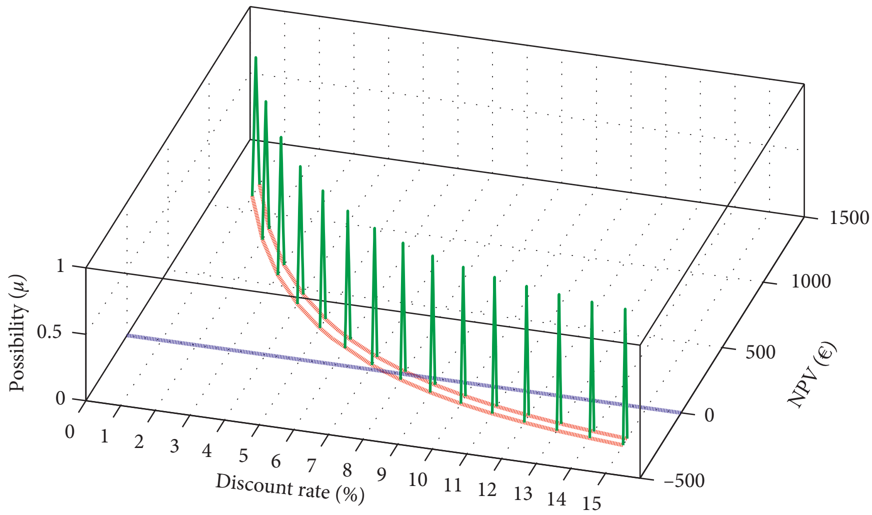

Figure 1: Three-dimensional fNPV graph.

where μfIRR is the membership function of the fuzzy internal rate of return, P_{xz} is the xz plane that is determined by the x and z axis at $y = 0$, and $\mu_{\mathrm{fNPV}_{i=0}^{R}}$ are all the membership functions of the fuzzy net present value from the discount rate of 0 to a selected value of R.

An example of such a three-dimensional plot is provided in Figure 2, in which five fNPV membership functions are plotted for their respective discount rates. The intersection of these five fNPV membership functions with $P_{xz}\,(y = 0)$ defines 5 points which provide an estimate for fIRR. In effect, 5 points of the fIRR are calculated for the given interest rates (7.4%, 7.6%, 7.8%, 8%, and 8.26%).

3.2. Computerization Process. In order to get the exact shape of fNPV and fIRR, mathematical operations must be performed on the α-level sets of the variables of CBA with the aid of a computer program. Hence, if a triangular fuzzy number is studied at 0.1 interval α-cuts with Equation (3), as seen in Figure 3, it is represented by 21 numbers: 10 for the optimistic values, 10 for the pessimistic, and 1 for the value of no uncertainty ($\alpha = 1$). Thereafter, there are two steps.

Step 1: calculate fNPV for a range of discount rates. The fuzzy cash flow is calculated based on the underlying fuzzy variables. Then, operations on fuzzy numbers are performed on the corresponding α-cut values between them. This process is repeated for a range of discount rates (from 0 to R) to calculate the respective membership functions for the fNPV.

Step 2: calculate fIRR based on the planar intersection with fNPV. The program searches to find the specific values of the discount rate for which a specific fNPV membership function crosses $P_{xz}\,(y = 0)$. Then, it loops over all the points of the α-cuts in order to find the two points in which there is a change of sign of the value of NPV. In Figure 3, we see that the intersection of fNPV with P_{xz} is between the two points of the α-cut levels of 0.3 and 0.4. The precise coordinates of the point of the intersection are calculated using the dot product formula for P_{xz} and the two other respective points. Understandably, the numerical precision of the calculation of fIRR depends on the increments of the discount rate as well as the selected number of α-cuts.

4. Case Study

In order to demonstrate the application of the model to civil engineering projects, it is applied to the data of a case study that is presented in the "Guide to Cost-Benefit Analysis of Investment Projects (Economic appraisal tool for Cohesion Policy 2014–2020)" of the European Commission [33]. The project concerns the construction of a new 16.4 km tolled motorway which is part of the Trans-European Network for Transport. The motorway will reduce traffic on an existing road which carries annual daily traffic of more than 18,000 vehicles. The motorway has 2 × 2 lanes (plus an emergency lane) with a width of 27.5 m, 3 junctions, 3 bridges (total length 2,200 m), 4 overpasses (total length 800 m), and 1 tunnel with two tubes (length 2,200 m). The socioeconomic analysis includes following monetised benefits, which are consistent with the project objectives, that are, faster travel on a safer road with separated carriageways, travel time savings, vehicle operating cost savings, environmental savings (CO_2 reduction), and accident cost savings [33]. Investment costs include the construction cost, whereas operating costs are the sum of maintenance costs with general expenses. During years 15–19, there are significant rehabilitation and renewal works on the motorway. At the end of the valuation period (30 years), the infrastructure retains a residual value. The resulting cash flows are shown in Table 1.

Hence, in socioeconomic analysis, the fuzzy net cash flow of Equation (7) is calculated as the difference between social benefits and costs:

$$\tilde{C}_n = \widetilde{\mathrm{TS}}_n + \widetilde{\mathrm{VOC}}_n + \tilde{A}_n + \tilde{E}_n - \widetilde{\mathrm{IC}}_n - \widetilde{\mathrm{OM}}_n, \quad (9)$$

where $\widetilde{\mathrm{TS}}_n$ is the time savings, $\widetilde{\mathrm{VOC}}_n$ is the vehicle operating costs savings, $\tilde{A}_n$ is the accident savings, $\tilde{E}_n$ is the

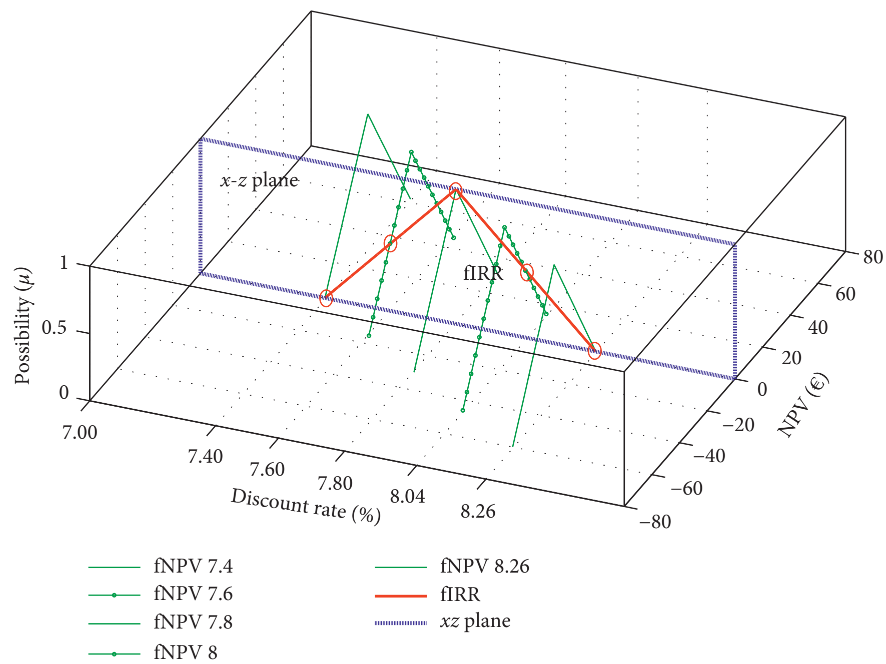

Figure 2: Definition and calculation of fIRR.

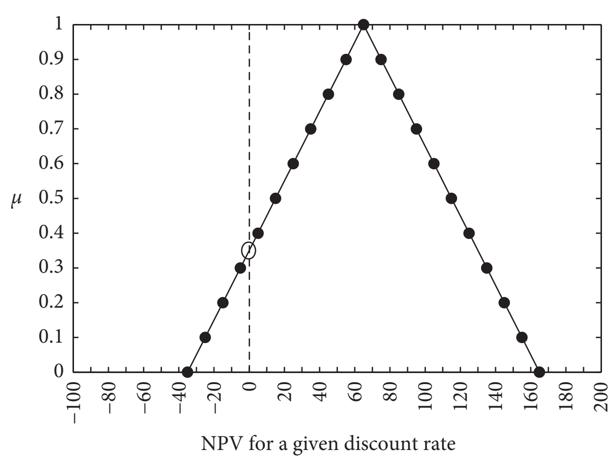

Figure 3: α-level sets of fNPV.

environmental savings (CO_2 reduction), $\widetilde{IC}_n$ is the investment cost, and $\widetilde{OM}_n$ is the operation and maintenance cost.

The fundamental concept is to model the uncertainty in all relevant parameters in the analysis of the cash flow as fuzzy numbers. As a result, the indices of the analysis will also be fuzzy numbers and consequently provide a basis for risk assessment. A sensitivity analysis reveals that the investment cost and the time savings are the most critical variables [33]. Thus, the risk analysis will study the scenario that the investment cost may be reduced by 5% or increased by 20%, whereas the time savings may be reduced by 30% or may be increased by 15%. Thus, the baseline variables of investment cost and operation and maintenance costs (in Table 1) are fuzzified by providing the optimistic and pessimistic values based on a percentage change valuation. Hence, for instance, a −5% and +20% uncertainty regarding uncertainty in the investment cost of the first year is represented as $\widetilde{IC}_1 = \langle -113.9, -94.9, -90.16 \rangle$, whereas as −30% and +15% uncertainty regarding the time savings in the 4th year are $\widetilde{TS}_4 = \langle 7.49, 10.7, 12.31 \rangle$. Crisp (nonfuzzy) operation and maintenance costs in the 4th year are represented as $\widetilde{OM}_4 = \langle -0.8, -0.8, -0.8 \rangle$. Overall, costs are denoted with a negative sign, whereas benefits with a positive sign.

The model aims to find the robustness of fNPV and fIRR in regard to fluctuations in time benefits and investment cost. Additionally, in order to interpret the graphs of fuzzy variables at different α-cuts which represent different levels of possibility, the following rough assumptions can be made: $\alpha = 1$ corresponds to no risk, $\alpha = 0.7$ to low risk, $\alpha = 0.5$ to medium risk, $\alpha = 0.3$ to high risk, and $\alpha = 0+$ to the most extreme scenario. Thus, in Figure 4, under deterministic analysis ($\alpha = 1$), the NPV would be 86 mil. € when considering a discount rate of 5%. However, in the absolute worst case which occurs with the simultaneous increase of investment costs and the reduction of time savings, the fNPV is −36 mil €. Similarly, in the best case, the fNPV will be 136 mil. € with a reduction of investment costs and an increase in time savings. The unevenness of the baseline variables creates the asymmetry in the graph.

Figure 5 plots the fNPV in three dimensions when the discount rate varies from 0% to 15%. From the graph, it can be seen that the values of fNPV approach zero near a discount rate of 4 to 9%. As such, it is imperative to examine this region in greater detail. Another interesting observation is that, at $r = 0\%$, the NPV varies between 342 and 687 mil. €. However, as the discount rate is increased, the difference between the optimistic and pessimistic scenarios is reduced dramatically, that is, at $r = 15\%$, the difference is only 80 mil.

Table 1: Baseline data for motorway construction [33].

Year	Costs (mil. €)		Benefits (mil. €)			
	IC_n	OM_n	TS_n	VOC_n	A_n	E_n
1	(94.9)	0	0	0	0	0
2	(92.1)	0	0	0	0	0
3	(57)	0	0	0	0	0
4	0	(0.8)	10.7	1.3	0.4	0.1
5	0	(0.8)	11.5	1.4	0.4	0.1
6	0	(0.8)	12.3	1.5	0.5	0.1
7	0	(0.8)	13.2	1.5	0.5	0.1
8	0	(0.8)	14.1	1.6	0.5	0.1
9	0	(0.8)	15	1.7	0.5	0.2
10	0	(0.8)	16	1.8	0.6	0.2
11	0	(0.8)	17	1.9	0.6	0.2
12	0	(0.8)	18	2	0.6	0.2
13	0	(0.8)	19	2	0.7	0.2
14	0	(0.8)	20	2.1	0.7	0.2
15	0	(6.9)	20.7	2.1	0.7	0.2
16	0	(6.2)	22	2.2	0.7	0.2
17	0	(5.8)	23	2.2	0.8	0.2
18	0	(5.2)	24	2.3	0.8	0.3
19	0	(4.4)	25	2.4	0.8	0.3
20	0	(0.8)	25.4	2.4	0.9	0.3
21	0	(0.8)	26	2.5	0.9	0.3
22	0	(0.8)	29	2.5	1	0.3
23	0	(0.8)	29	2.6	1	0.4
24	0	(0.8)	30	2.6	1	0.4
25	0	(0.8)	30.5	2.7	1	0.4
26	0	(0.8)	34	2.8	1.1	0.4
27	0	(0.8)	35	2.8	1.2	0.4
28	0	(0.8)	36	2.9	1.2	0.5
29	0	(0.8)	37	2.9	1.2	0.5
30	151	(0.9)	37.7	3	1.2	0.5

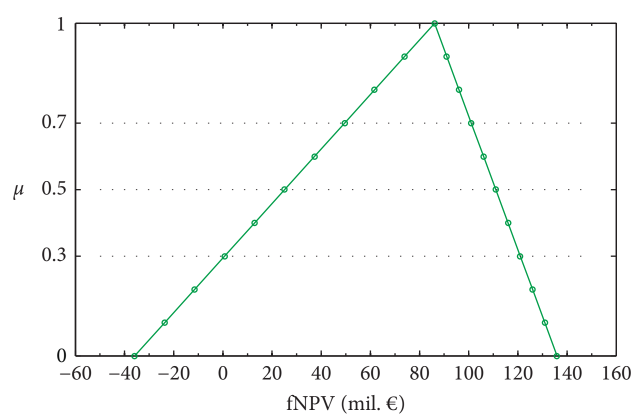

Figure 4: fNPV for a discount rate of 5%.

€. Eventually, the optimistic and pessimistic scenarios both yield negative values for NPV.

Figure 6 provides a closer insight as to how the fIRR can be formed by the intersection of P_{xz} (at $y = 0$) with the fuzzy sets of fNPV. It shows 25 NPV membership function graphs that correspond to discount rates from 4% to 8.8% at 0.2 increments. The computer program calculates the intersection of every NPV membership function with P_{xz}. Then, the fIRR is formed by connecting 22 points since 3 membership functions do not intersect with P_{xz}. Understandably, the fIRR will be represented with higher resolution if the discount rate increments are at 0.1 or lower.

Figure 7 shows a two-dimensional plot of the three-dimensional graph as if it were seen from an "aerial view" above the z axis. It is apparent that the spread of the NPV membership functions gets narrower as the discount rate increases. It is also evident how the fIRR is formed from the intersection of various fNPV membership functions with P_{xz} (NPV = 0). Finally, it can be seen how 3 fNPV membership functions for the discount rates of 4%, 8.6%, and 8.8 % do not intersect with P_{xz}.

The methodology has succeeded in calculating fIRR. Thus, Figure 8 provides a two-dimensional plot of the fIRR that was calculated previously. Essentially, the crisp value of IRR is 7.2% but because of the presence of uncertainty, it varies from 4.2% to 8.4%. Hence, there is a significant possibility that the outcome of the project will be significantly lower or somewhat higher than what initially expected.

5. Discussion

5.1. Interpretation of Results. The ability to plot and study fNPV in three dimensions is very promising. It is now possible to see how fNPV and fIRR are related to the discount rate. Hence, alternative projects should not only be compared based solely on a single fNPV but also on the way the fNPV changes in regard to the discount rate. Also, the fIRR can be calculated in an intuitive and very effective manner. As expected, there is not a single value of a discount rate that sets NPV equal to zero. Overall, negative values of NPV or low values for IRR indicate that there are significant risks in the project. Hence, risk control strategies should be employed, or funds should be directed to alternative investments.

In the case study, the uncertainty analysis reveals the problems stemming from the inability to control construction cost and estimate the future benefits. Individually, the tunnel costs 80 mil. € or approximately one-third of the total construction cost. Even though there are several geological studies, it may not be possible by the project manager to control the cost escalation arising from adverse geological conditions that can't be predicted [33]. Also, it is unlikely that the original estimation of benefits will be correct due to the inherent volatility of traffic demand.

Decision-maker's choice depends largely on his their attitude towards risk [34]. Decision-makers should have the best tools available to understand and comprehend the risks they are undertaking. Thus, they should be able to understand the relation of the input variables to the project outcome. Also, it is desirable that they can compare different projects to each other. As such, the fuzzy project performance indicators (fNPV and fIRR) of alternative projects can be compared with Equations (3)–(5).

5.2. Comparison to Stochastic Analysis. It is very interesting to compare the methodology for uncertainty modelling with

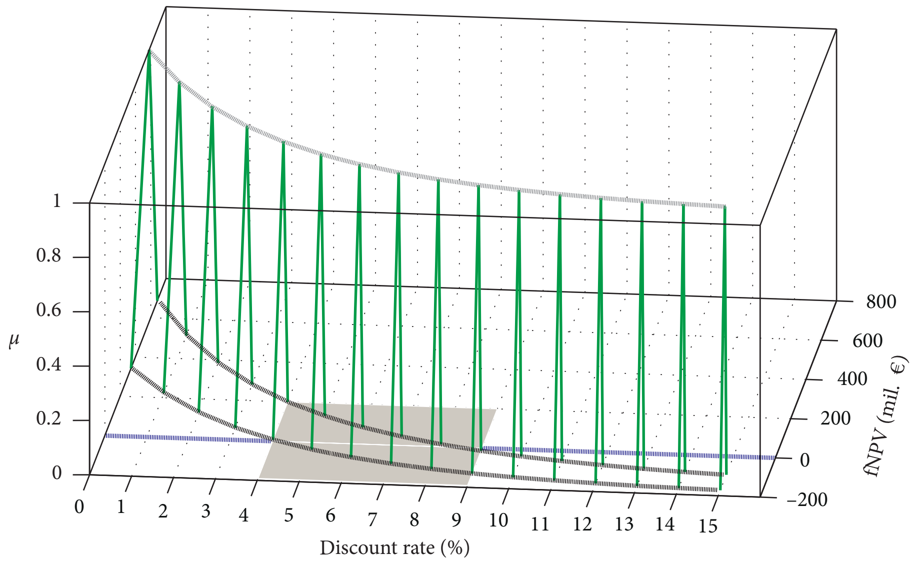

Figure 5: 3D plot of fNPV for various discount rates.

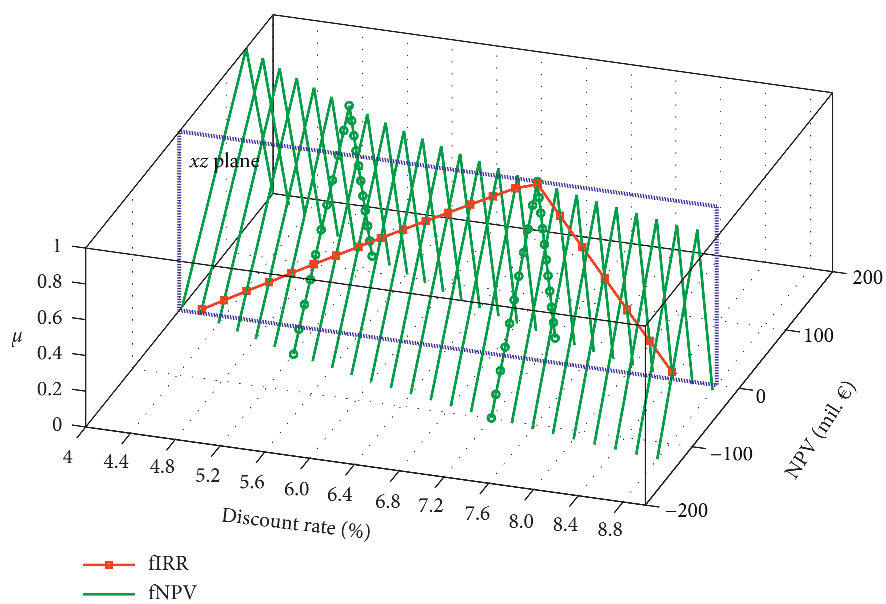

Figure 6: Calculation of fIRR.

fuzzy set theory to that of stochastic analysis with Monte Carlo analysis. Overall, the fuzzy methodology presents the following advantages: (a) computational efficiency: the results of fNPV and fIRR are derived through a single analytical calculation, contrary to Monte Carlo analysis that requires thousands of iterations; (b) repeatability: in Monte Carlo analysis, the results of every simulation are moderately different from each other due to the randomness of numbers that are generated by computers. On the other hand, for a given set of input variables, the results of a fuzzy analysis are 100% repeatable; and (c) uncertainty aggregation: project stakeholders may often need to assess the total risk of a group of projects or that of a programme. With fuzzy set theory, it is very straightforward to add indicators from many projects and thus attain an aggregated fuzzy performance indicator—something which is not feasible with probability distributions.

5.3. Fuzzy AIRR. A fascinating research question is if the proposed Euclidean space can be useful in studying the AIRR or its fuzzy equivalent. Since the AIRR is defined as the ratio of total profit to the total capital invested and it is calculated by dismissing the IRR equation, the Euclidean space does not present an advantage in its calculation which can be done quickly. However, in examining the graphs of

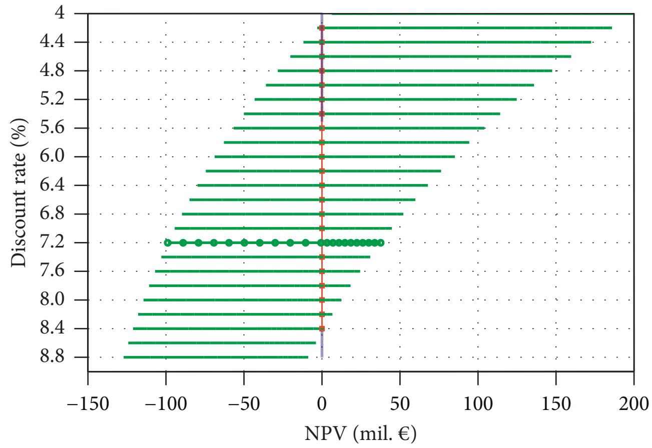

Figure 7: Aerial view of 3D fNPV graph for the motorway.

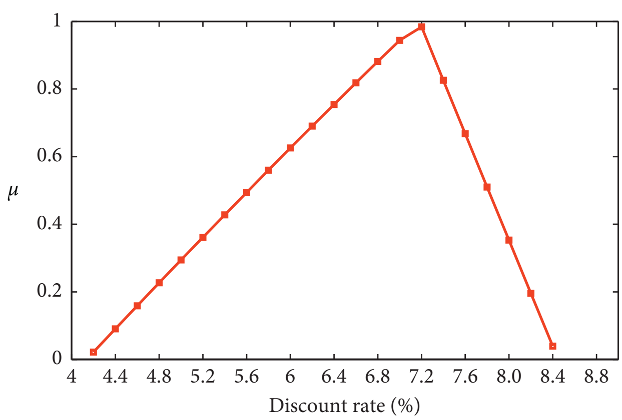

Figure 8: 2D plot of fIRR.

fuzzy NPV and AIRR, there may be considerable advantages in studying their relationship in the Euclidean space. Specifically, Magni [35] proposed the concept of an "isovalue line" which is essentially an indifference curve that supplies the same NPV on a two-dimensional graph of the AIRR vs. capital invested. Potentially, the concept of the "isovalue line" could be extended to that of an "isovalue surface" if a three-dimensional graph is employed (x axis: invested capital, y axis: AIRR, and z axis: possibility). The graphical tool could significantly enhance intuition and understanding of risks in projects. Thus, future research may be targeted towards studying fuzzy AIRR with three-dimensional graphs.

6. Conclusions

Using a Euclidean space, this paper presents an alternative approach to studying uncertainty in NPV and IRR based on fuzzy set theory. Its assumptions are realistic and intuitive for engineers; it has low mathematical complexity and is much simpler to computerize than stochastic risk analysis. With three-dimensional fNPV and fIRR graphs, project evaluation and selection can be seen for the first time from a different perspective. Also, the paper has succeeded in formulating a novel approach to calculating fIRR. These tools may help in examining projects with greater scrutiny to determine the robustness of the decision indices.

Finally, future research can be directed in formulating a holistic methodology that incorporates fIRR and fNPV with fuzzy project scheduling, fuzzy cash flow analysis, and benefits realization in an advanced management system. Additionally, the use of three-dimensional graphs may potentially increase the understanding of the newly introduced AIRR. Most importantly, fuzzy risk analysis should be seen as a core methodology that when coupled with other emerging techniques can increase the quality and realism of estimation data leading to the advanced management of projects.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Developing an IFC-Based Database for Construction Quality Evaluation

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Quality evaluation and control are increasingly important concerns in construction projects. Construction quality evaluation, as a systematic method, must be discussed in light of quality information extraction and storage, while a traditional construction quality control program cannot meet these requirements. In moving beyond quality indicators to evaluate quality performance that is comparable across construction entities, two fundamental factors must be considered: quality information standardization and multiquality data integration. The purpose of this study is to extend the interoperability of a construction quality database in the evaluation process by employing the industry foundation classes (IFC) data model. Taking a cast-in-place steel-concrete structure as an example, this study explores the implementation of building information modeling (BIM) in quality management and proposes integrated solutions to improve current quality management processes with the assistance of an IFC-based working environment. To better utilize the performance of the BIM model and database on construction quality control, various BIM-based evaluation frameworks are proposed. Also, this paper discusses how these IFC and neutral network models operate together to facilitate construction quality management. Project participants can better understand quality progress and collaborate more effectively, thanks to a visualized data format. The objective of evaluating the proposed model is to understand the effectiveness of an IFC-based database when implemented in practice. A questionnaire was developed considering the opinions of construction firms and design institutes regarding identified factors. In designing an IFC-based quality database, the method proposed in this study reduces the complexity of the database substantially and improves quality evaluation efficiency.

1. Introduction

Quality management is an approach to management that improves the effectiveness, flexibility, and competitiveness of an entity or project [1]. The notion of quality and its importance to the construction industry has been an area of great concern for many years [2]. The construction industry is widely criticized for low-quality delivery of construction projects, especially in terms of finished products, as well as for the processes used during the project design and construction stages [3]. Significant time and costs can be spent correcting problems during the snagging process, and most projects either suffer from time overages, cost overages, or both. Shao and Fu [4] suggested that the lack of an integrated evaluation method and a poor attitude towards quality on behalf of engineering stakeholders can lead to snagging problems.

In the construction industry, successful and long-term implementation of quality programs has been hampered by the fact that, unlike safety, no single measure and integrated expression of quality is applicable to the lifecycle of construction projects. Past attempts to monitor quality within construction have focused on identifying key factors because quality is subjective: what one person may accept as high quality may be considered insufficient by another. In addition, previous efforts have evaluated quality via key factors, such as the number of punch list items, the number of requests for information, or the number of callbacks for projects. The problem with only focusing on quality factors or indicator selections is that it is impossible to connect quality factors with the given attributes of a construction project, especially in terms of locating and distinguishing indicators of unsatisfactory quality associated with a specific structural element. Therefore, a comprehensive approach to indicator analysis integrated with multidimensional data is required to better understand quality management in the evaluation process. Furthermore, to go beyond quality indicators and evaluate quality performance that is comparable across construction entities, two processes are paramount: quality information standardization and multiquality data integration.

Quality evaluation and control represent increasingly important concerns for project managers. Construction quality evaluation as a systematic method must be discussed in light of quality information extraction and storage, whereas a traditional construction quality control program cannot meet such requirements [5]. Building information modeling (BIM) has gained popularity in the AEC industry [6]. BIM is a new technology that can control the construction process, construction conditions, and model links to resolve communication problems between relevant parties. Due to the consistency of design data and quality data, the potential of BIM implementation has been supported in quality management, namely, when presenting multidimensional data [7]. Nepal et al. [8] found that the rapid development of BIM has cultivated numerous opportunities for design and construction.

To effectively retrieve and utilize multidimensional information in construction quality evaluation via BIM, industry foundation classes (IFC), an international standard in BIM modeling, can be used to share data [9–11]. However, IFC standards do not currently accommodate entities with unstructured quality-related information or relationships involved in the quality database. This study seeks to realize the requirements of visualization and data integration in construction quality evaluation. Specifically, it applies the visual evaluation method to render the evaluation process more effective and convenient in identifying quality problems while providing comprehensive, reliable data resources for quality management of construction enterprises and construction administrators. These developments can further improve quality management, playing an important role in the standardization, digitization, and informatization of construction project management. Finally, the proposed method was evaluated by construction quality management specialists.

2. Related Study

BIM technology offers new approaches to construction quality evaluation; however, unified standards for the development of a quality system are lacking [12], as not all quality information can be integrated into a single model due to different data formats that may be tied to other data resources, such as quality records or design specifications. To overcome this limitation, IFC presents a solution to integrate and standardize all quality information, particularly with respect to user-required data mapping mechanisms [13].

Due to the absence of unified standards across application fields, the integration of different quality information sharing systems between databases is poor [14]. Currently, IFC data are managed by a file system, including files in ifc [15] and ifcXML [16] formats. Recently, studies on database storage of IFC data have been conducted to overcome deficiencies in file-based storage with some achievements. Since the traditional database structure does not support storage of object-type data, conflicts between a relational database structure and IFC element features are unresolved [17]. Therefore, the main goal and contribution of this paper lie in the creation of an IFC-based database consisting of qualitative quality data that can serve as the basis for construction evaluation management. Moreover, by designing this database, a few tables can store all IFC instances without the need to create a table for each entity in IFC; this feature significantly reduces the complexity of the database and improves quality evaluation efficiency. On the contrary, unified standards for the development of a quality system are lacking [12], as not all quality information can be integrated into a single model due to the different data formats which may be linked to other data resources, such as quality records or design specifications. Mazairac and Beetz [18] believed that the large amount of information generated by the integration of models from different disciplines in a common virtual model also increases the size and complexity of data repositories. Industry foundation classes (IFC) seem to be a solution to integrate and standardize all quality information, particularly with respect to data mapping mechanisms required by the user [13].

Meanwhile, because there are no unified standards across the application field, the integration of different quality information sharing systems between databases is poor [14]. Currently, IFC data are managed by file system, including ifc [15] and ifcXML [16] format files. In recent year, studies on database-based storage of IFC data have been continuously carried out to overcome the deficiencies in file-based storage and have made some achievements. But since traditional database structure does not support the storage of object-type data, the conflicts between relational database structure and element features in IFC are still not resolved [17]. Therefore, the main goal and contribution of this paper lies in the creation of an IFC-based database consisting of qualitative quality data that can become the basis for construction evaluation management. Moreover, by designing the database, a few tables can be used to store all IFC instances and no more need to create a table for each entity in IFC, which not only significantly reduces the complexity of the database but also improves quality evaluation efficiency.

3. Methodology

This study aims to extend the interoperability of construction quality database in evaluation process by employing the industry foundation classes (IFC) data model. To achieve this, by referring to construction quality inspection and acceptance specification, we connect IFC data and BP neural network algorithm to construction quality evaluation to improve the efficiency and accuracy of evaluation. Considering the large number of quality evaluation database created in BIM domain, we focus on two scenario analysis process: (1) to realize specifically the IFC data mapping in construction quality domains which include evaluation indicators, quality score, and quality grade; (2) to realize all quality data involved in evaluation need to be classified and unified encoded to construct the quality evaluation database. Then, we try to discuss the logical framework and physical structure design of the database to integrate the heterogeneous construction quality data. Finally, we use a case study to verify the methods proposed in this study.

In previous studies, researchers have developed their own approaches to obtain the quality data of construction projects. Some studies focus on limited elements such as doors, windows, and spaces with corresponding descriptive information. Many of these approaches are practice specific. However, for BIM projects, there is a need to create quality data for all model elements and to create it to standards that allow structured data to be utilized efficiently and reliably by the evaluation process. In this study, we define quality data in IFC-based parameter fields and convert related information directly into IFC and BP models. This means we aligned evaluation information with open international standards IFC (ISO 16739:2013) according to which the BP neural network model can be trained and tested as expected, and then the approved model can be used to predict the construction quality score. This process has the potential to reduce the need for collecting manually big data of construction projects, particularly as more design software adopt open principles. Finally, this approach obtains the quality score and grade according to the open data to be mapped.

We created a workflow (Figure 1) illustrating the prototypical framework to build a construction quality database with essential data sources from graphical evaluation, parameter evaluation, IFC model, construction field data collection, and user information. To collect reliable data, the approach depended on effective IFC file extension for construction quality and adding a description to the construction site to support the corresponding operations (extract, transform, and load) by users. Therefore, mapping adds the ability to take a piece of structured data that already exists in the BIM model and put it into a unified field related to construction quality. Any piece of IFC data can therefore automatically be placed into a corresponding evaluation program. Furthermore, this paper discusses the classification and encoding approach to enter data into the evaluation database, which uses the conceptual model proposed in this study to model the input data required and produced in the previous stage from a construction quality perspective to achieve integrated construction quality management.

4. Quality-Oriented Evaluation Model Based on IFC and BP Neutral Network

4.1. Selection of Construction Quality Evaluation Index. To compute the value of quality content, it is important to establish an evaluation indicator system that accounts for performance testing, quality records, allowable deviation, and appearance quality. As quality has no specific definition, briefing documents must clearly outline the necessary quality level. Official documentation, standards, and specifications can aid in the appraisal of construction entities. Taking the cast-in-place steel-concrete structure as an example, referring to the *Acceptance Standard for Construction Quality of Constructional Engineering (GB 50300-2013), Acceptance Specification for Construction Quality of Concrete Structure Engineering (GB 50204-2015), Evaluation Criteria for Construction Quality of Constructional Engineering (GB/T 50375-2016)*, and work by Zhu and Zhang [19] and Fu et al. [20], 16 quality evaluation indicators were determined among the aforementioned four categories (i.e., performance testing, quality records, allowable deviation, and appearance quality) to reflect the overall appraisal of construction quality, represented by the 17th indicator as shown in Table 1.

4.2. Overall Appraisal of Construction Quality in BP Neural Network Model

4.2.1. Evaluation of Model Structure. A single hidden layer neutral network is adopted in this paper. The evaluation model includes an input layer, single hidden layer, and output layer. The index values in Table 1 can be used as the input parameters for the BP neural network model, so the number of nodes in the input layer is 16. The quality scores (a hundred-mark system) of the steel-concrete structure can be obtained through the evaluation model; thus, the number of nodes in the output layer is 1. The number of nodes in the hidden layer is usually determined by a formula $L = \sqrt{m + n} + a$, where L is the number of nodes in the hidden layer (a positive integer), m and n are the number of nodes in the input and output layer, respectively, and a is a constant between 0 and 10. According to this formula, the number of nodes in the hidden layer of the BP neural network model is a constant between 5 and 14. The constants in this range must be tested, and the constant corresponding to the optimal training result is ultimately selected as the number of nodes.

4.2.2. Sample Data Classification. Classification is based on the initial value of each indicator as shown in Table 2. The first-level indicators were marked using a 10-point system based on experts' opinions. The indicator values in the 2nd level were obtained from *Construction quality acceptance records* of the inspection lot in the steel-concrete structure. The 3rdlevel indicator values represent the appearance quality of structural entities, obtained from *Construction appearance-quality acceptance records* in the inspection lot. In terms of construction quality acceptance, observation methods are normally used to verify whether the evaluation indicators satisfy specifications and design requirements. The 17^{th} indicator "overall appraisal" usually classifies the inspection results as either *Good* or *General*. This paper utilizes a percentage where the number of inspection sites labeled as *Good* occupies all sites to achieve a quantitative description.

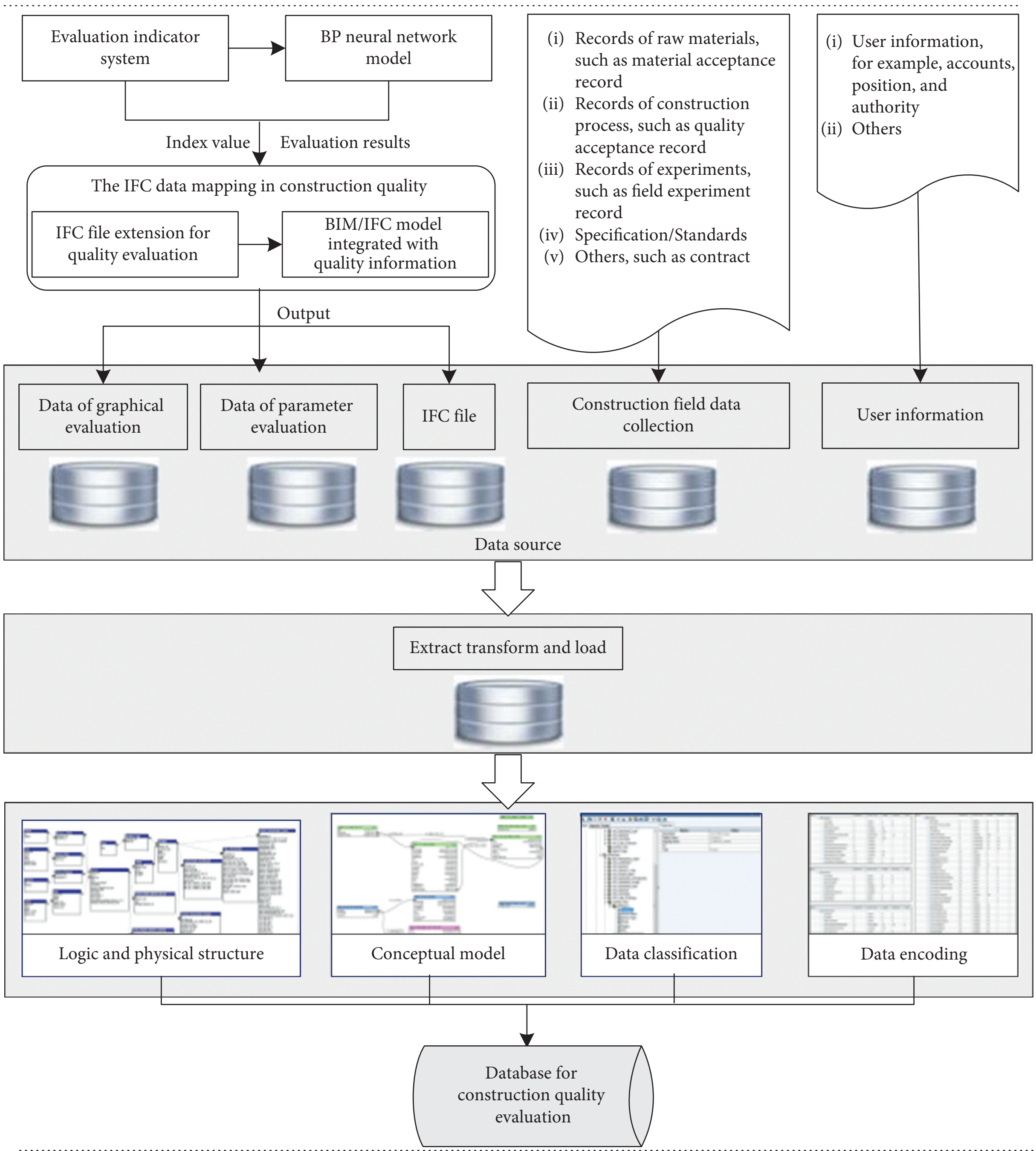


Figure 1: Method proposed.

4.2.3. MATLAB Implementation of the Evaluation Model. In this study, 24 groups of sample data were collected through investigation and surveys, as shown in Table 3. MATLAB R2016b software was employed to establish the construction quality evaluation model based on the BP neural network. The training situation and graphic outputs are shown in Figure 2. The processing time of the neural network was 15 seconds, and it achieved optimal output over 10706 rounds of training with a mean squared error (MSE) of $9.99 * e^{-9}$, gradient of $3.49 * e^{-5}$, and degree of fit reaching 0.99642. The expected values of the test samples were 86.15, 91.50, 89.80, and 96.30, respectively, and the predicted results were 86.33 93.02, 93.04, and 95.60. The absolute error was in the range of −0.7 to 3.2 with error rates of 0.21%, 1.66%, 3.61%, and −0.73%. The absolute value was less than 5%. The prediction results satisfied the precision requirements. According to *Evaluation Criteria for Construction Quality of Constructional Engineering* (GB/T 50375-2016), an overall appraisal of structural quality of 85 and above is rated as “Good”.

4.3. IFC Data Mapping in Construction Quality Domain. In this work, a formalization structure is suggested for database tables to facilitate the exchange of IFC-based evaluation indicator information via the information

Table 1: Evaluation index for construction quality of reinforced concrete main structure.

No.	Evaluation indicator	Structural element	Evaluation item	Description of indicator
1	Concrete strength	Beam, slab, column, wall	Performance test	The concrete strength of the structure entity shall be reflected to meet the specifications and design requirements
2	Reinforcement cover thickness deviation	Beam, slab, column, wall		The measured deviation value of the cover thickness of longitudinal carrying bars in the structural entity is within the range of ±5 mm
3	Column cross section dimension deviation	Column		The measured deviation value of the sectional dimension of cast-in-place reinforced concrete columns should be within the range of (+10, −5) mm
4	Wall thickness deviation	Wall		The measured deviation value of wall thickness of cast-in-place reinforced concrete should be within the range of (+10, −5) mm
5	Beam depth/width deviation	Beam		The measured deviation value of the beam depth and width of cast-in-place reinforced concrete shall be within the range of (+10, −5) mm
6	Plate thickness deviation	Slab		The measured deviation of slab thickness of cast-in-place reinforced concrete shall be within the range of (+10, −5) mm
7	Completeness of raw material record	Beam, slab, column, wall	Quality records	The material qualification certificate, the incoming acceptance record and the reexamination report shall be complete
8	Completeness of construction record	Beam, slab, column, wall		The record of the working performance of premixed concrete, the concrete construction record, the reinforcement installation record and the construction quality check, and acceptance record shall be complete
9	Completeness of test record	Beam, slab, column, wall		The test report of concrete mix proportion, the strength report of concrete specimen, and the test report of steel joint connection should be complete
10	Axis deviation	Beam, column, wall	Allowable deviation	The measured deviation value of the axis position of structural element should not exceed 8 mm
11	Elevation deviation	Beam, slab, column, wall		The measured deviation value of storey height elevation shall be within the range of ±10 mm
12	Verticality deviation	Column, wall		The measured deviation value of height and verticality of component should not exceed 10 mm
13	Planeness deviation	Beam, slab, column, wall		The measured deviation value of the surface evenness of the component shall not exceed 8 mm
14	Crack	Beam, slab, column, wall	Appearance quality	Any defects that affect the transmission performance of the structure should not exist in joints of the entity
15	Joint reliability	Beam, slab, column, wall		Any serious internal steel exposure should not exist in the structure entity
16	Exposed reinforcing steel	Beam, slab, column, wall		
17	Overall appraisal			Integrate 16 indicators to evaluate construction quality

provider (i.e., quality-related information stored in the IFC model) and information receiver (i.e., heterogeneous database integration system). All quality evaluation data are uniquely identified via unit ID, which maintains the information exchange between the IFC model and database tables. Under this condition, a new type of ID is necessary along with mapping between process resources and IFC objects to support cost-information exchange. Therefore, IFC data mapping and extension comprise a primary step to link evaluation information generated in the IFC model with database tables.

As shown in Figure 3, in terms of standard level, quality evaluation information has to be extended and expressed in IFC standards. In this process, EXPRESS-G as a graphical modeling notation is developed within STEP and used for IFC definition. It is used to identify classes, the data attributes of classes, and the relationships that exist between classes. In terms of the application level, Revit software for BIM was employed in this paper to describe quality attributes as additional parameters in the BIM model, thereby integrating evaluation information in IFC documents as shown in the exported IFC validation document.

4.3.1. IFC Extension Process Based on AttributeSet of Construction Quality. Evaluation information related to

Table 2: Classification of construction quality evaluation indicators.

Category	Index	Item
First category	Concrete strength	Performance test
	Completeness of raw material record, completeness of construction record, completeness of test record	Quality records
Second category	Reinforcement cover thickness deviation, column cross section dimension deviation, wall thickness deviation, beam depth/width deviation, plate thickness deviation	Performance test
	Axis deviation, elevation deviation, verticality deviation, planeness deviation	Allowable deviation
Third category	Crack, joint reliability, exposed reinforcing steel	Appearance quality

Table 3: BP neural network sample data.

Evaluation index no. (Ei)	Ei1	Ei2	Ei3	Ei4	Ei5	Ei6	Ei7	Ei8	Ei9	Ei10	Ei11	Ei12	Ei13	Ei14	Ei15	Ei16	Ei17
1	10	3.07	4.82	6.6	5.4	5.33	10	10	10	3.77	3.95	4.91	3.68	1	1	0.9	96.3
2	10	2.94	4.5	5.92	5.1	5.29	9	10	9	3.42	2.6	4.55	5.11	0.95	0.9	1	94.9
3	8.5	3.88	6.27	5.5	7.19	5.5	8.5	8	8.5	5.26	6.1	7.33	6.54	0.8	0.85	0.8	83
4	8.5	4.17	6.4	7.39	6.4	6.96	7	8.5	8	4.92	5.97	8.5	7.29	0.8	0.92	0.8	79.75
5	7	4.28	6.97	7.21	6.99	8.1	8	8	7	7.2	8.9	8.94	7.11	0.84	0.9	0.95	76.7
6	7.5	4.05	7.83	5.5	7.93	5.22	7	9	8.5	6.91	9.22	9.59	7.36	0.82	0.88	0.8	77.75
7	8	4.39	7.1	8.87	8.2	9.24	8.5	8	7	7.09	8.36	8.91	6.8	1	0.91	0.95	79.05
8	10	2.97	5.15	4.2	4.96	5.52	9	9	9	3.42	4.22	3.88	4.07	0.8	0.95	0.9	93.15
9	9	4.05	7	7.27	6.9	6.08	8	9	7	6.18	7.01	9.12	7.03	0.9	0.84	0.8	80.1
10	10	3.31	4.91	6.11	4.92	8.34	9	10	10	3.81	4	6.21	5.7	0.85	0.9	0.86	92.3
11	8.5	4.02	5	6.6	4.37	5.13	8.5	9	8.5	5.3	6.12	7.52	6.21	0.8	0.8	1	85.15
12	7	4.67	7.44	5.59	7	7.19	7	8	7	7.1	8.76	9.71	7.6	0.85	0.9	0.9	73.9
13	9	3.04	5.11	4.9	5.34	4.98	8.5	10	8.5	4.05	2.92	5.8	4.5	0.82	0.85	0.8	89.95
14	8.5	3.95	6.44	3.92	7.02	5.71	9	10	10	4.3	6.97	7.17	6.22	0.9	0.9	0.8	87.65
15	9	4.01	6.67	5.5	5.41	7.32	7.5	8.5	8.5	3.59	6.16	6.93	5.63	0.95	0.94	0.85	86.15
16	10	3.4	5.66	4.74	6	7.99	10	10	9	4.89	5.05	5.3	4	0.85	0.8	0.9	91.5
17	9	3.25	7	8.81	5.03	6.77	9	10	8.5	7.29	8.17	8.69	7.6	0.8	0.95	0.85	85.35
18	10	3.5	7.83	5	7.95	5.2	10	9	9	4	5.26	5.61	3.9	0.9	0.9	1	91.85
19	10	3.44	5.16	6.11	6.81	4.73	10	10	10	6.5	9.73	9	7.4	0.8	0.82	0.8	88.3
20	8.5	4.1	5.55	5.45	5.17	6.59	9	10	9	6.11	6	7.95	7.03	0.85	0.8	0.95	85.35
21	9	4.34	6.77	6.65	7	8.09	10	10	10	6.08	9.29	9.19	7.83	0.9	1	0.9	86.6
22	10	3.91	6.71	8.19	7.22	4.54	10	10	9	4.07	3.87	4.96	6.6	0.85	0.8	0.9	89.8
23	9	3.19	6.9	4.15	5.02	5.54	10	10	9	5.01	8.8	8.36	7.73	0.85	0.8	0.8	87
24	8.5	3.02	3.95	5.9	5.06	7	9	10	9	5.5	8.14	7.9	7.11	0.93	0.85	0.9	86.15

construction quality based on the IFC file extension describes the quality of the beam, plate, column, and wall, which are collectively regarded as the entity in the IFC model. This evaluation information is equivalent to entity characteristics described by the IFC standard. The existing IFC4 standards already include standardized definitions of beams, plates, columns, and walls. In this paper, the extension mechanism based on PropertySet was utilized to extend the quality attributes. The property set is a container class that holds specific properties within an IFC resource file. This extension approach was adopted because it was unnecessary to change the system structure of the original IFC standard, and the extension satisfied the requirements of incorporating evaluation information into the IFC standard. This approach was therefore convenient and feasible; the specific extension process is displayed in Figure 4 and proceeds as follows. First, the corresponding entity, attribute, and their relationship in the IFC standard must be determined according to the characteristics of quality evaluation in the structure construction. Second, attribute sets must be categorized according to different characteristics of the entities. Finally, attribute sets must be defined in terms of construction quality to complete the extension process of evaluation information based on the IFC.

(1) Identification of IFC Entities and Properties. The correspondence between the structural elements including beam, plate, column, wall, and the IFC entities are shown in Table 4. Each entity in a database is described by certain properties. Properties refer to pieces of element information on an entity required for processing via quality evaluation. Each quality evaluation indicator and overall appraisal calculated by the BP model align with the entity attributes. The overall appraisal also applies to its child elements' property set.

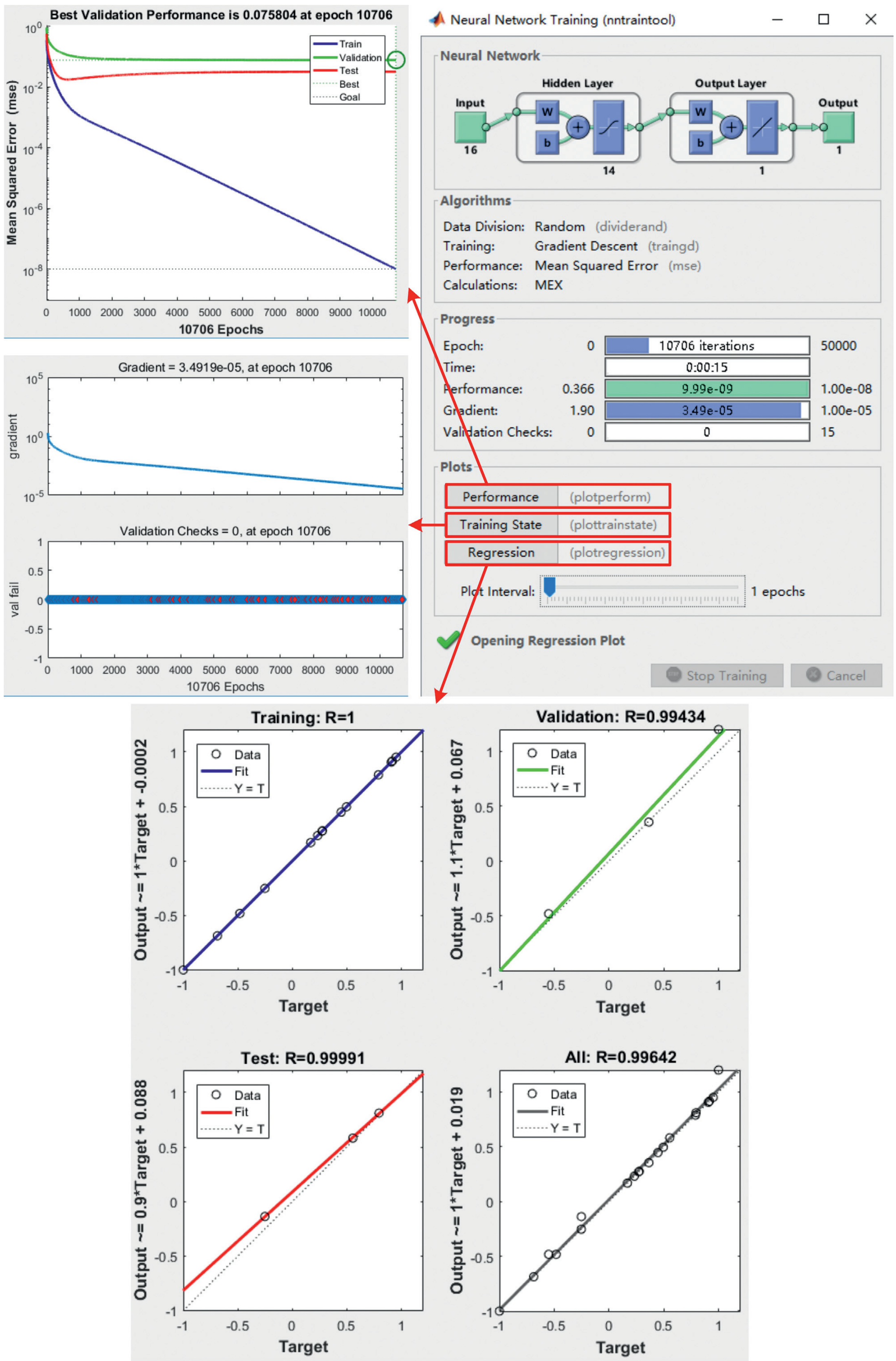


Figure 2: BP neural network training.

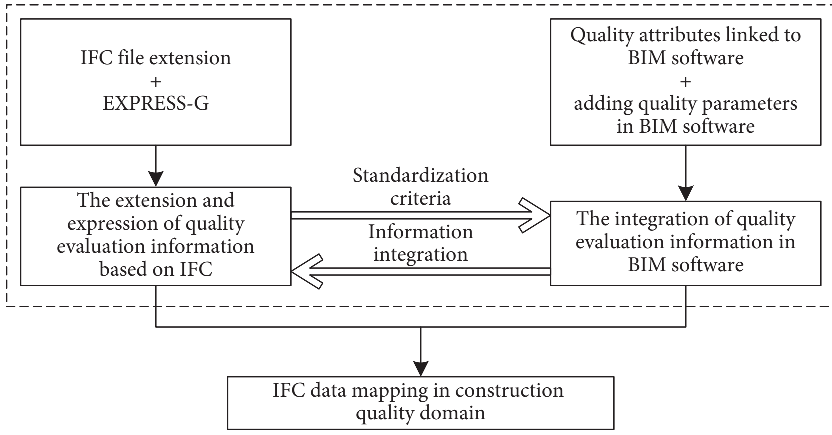


Figure 3: Implementation of IFC data mapping.

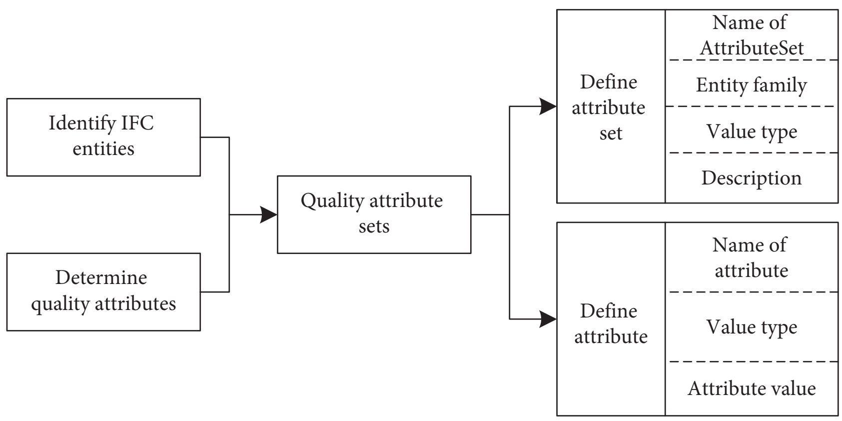


Figure 4: IFC extension process based on AttributeSet

(2) Determination of IfcPropertySet. A property set is a collection of attributes belonging to a particular entity. The quality attributes in this paper describe quality characteristics of structural elements; thus, IfcPropertySet is determined by four categories including PSet_OnsiteReinforcedConcreteBeam, PSet_OnsiteReinforcedConcreteSlab, PSet_OnsiteReinforced ConcreteColumn, and PSet_OnsiteReinforcedConcreteWall. The properties of each property set can be selected by referring to each evaluation indicator and structural element in Table 1.

(3) Definition of IfcPropertySet. Per the IFC standard, major entities of structure elements including columns, walls, beams, and plates are separated into a general definition and a specific specialization to represent the standard entities for a parametric exchange of shape, material, and underlying element type [21]. Some property sets, such as the 17 quality attributes listed in Table 1, are excluded from the IFC specification and lack a predefined set of properties indicated by structure element assignment. The definition of an IfcPropertySet includes a name, entity family, applicable type of value, and description, as shown in Tables 5–8. A definition and illustration of how IFC properties can be used to structure external library quality information is shown in Figure 5, in which the property type and value are determined by the quantized results of the quality evaluation indicators in Table 3. Various properties of the IFC entities are indeed a set of instances which are encapsulated in an IfcPropertySet entity. IfcPropertySet is a container class that holds properties within a property tree. This allows adding user-defined properties to IFC elements or types. In this study, four property sets "PSet_OnsiteReinforced ConcreteBeam," "PSet_OnsiteReinforced ConcreteWall," "PSet_OnsiteReinforced ConcreteColumn," and "PSet_ OnsiteReinforced ConcreteSlab" within the property set are defined as part of the standard. In this example, an on-site reinforced concrete model is structured as an instance of IfcPropertySet, and its properties are instances of the subclasses of IfcProperty. IfcObjectReference and IfcLibraryReference reference the property value.

Table 4: The correspondence between structural elements and IFC entities.

Mainbody structural component	Beam	Slab	Column	Wall
IfcEntity	IfcBeam	IfcSlab	IfcColumn	IfcWall

4.3.2. Expression of Quality Evaluation Information Based on IFC. After completing the IFC extension of quality

Table 5: The definition of IfcPropertySet of cast-in-place reinforced concrete beam.

AttributeSet name	PSet_OnsiteReinforcedConcreteBeam
Entity family	IfcBeam
Application type of value	IfcBeam/Userdefined/OnsiteReinforced ConcreteBeam
Description	Properties in this property describe quality of the on-site reinforced concrete beam, which can provide the basis for construction quality evaluation

Table 6: The definition of IfcPropertySet of cast-in-place reinforced concrete slab.

AttributeSet name	PSet_OnsiteReinforcedConcreteSlab
Entity family	IfcSlab
Application type of value	OnsiteReinforcedConcreteSlab
Description	Properties in this property describe quality of the on-site reinforced concrete slab, which can provide the basis for construction quality evaluation

Table 7: The definition of IfcPropertySet of cast-in-place reinforced concrete column.

AttributeSet name	PSet_OnsiteReinforcedConcreteColumn
Entity family	IfcColumn
Application type of value	OnsiteConcreteColumn
Description	Properties in this property describe quality of the on-site reinforced concrete column, which can provide the basis for construction quality evaluation

Table 8: The definition of IfcPropertySet of cast-in-place reinforced concrete wall.

AttributeSet name	PSet_OnsiteReinforcedConcreteWall
Entity family	IfcWall
Application type of value	OnsiteConcreteWall
Description	Properties in this property describe quality of the on-site reinforced concrete wall, which can provide the basis for construction quality evaluation

evaluation information, it is necessary to further describe the quality information. EXPRESS-G is a graphical modeling notation developed within STEP and used for IFC definition. In this study, it was used to identify the data attributes of IFC quality classes and the relationships that exist between classes as shown in Figure 6 [22–25]. Considering the five entity classes of IfcProduct, IfcElement, IfcBuildingElement, IfcPropertySetDefinition, and IfcPropertySet, an inheritance relationship can be expressed by thick lines between two adjacent entity classes, with circles directing to its subclasses. The relationship between IfcPropertySet and IfcEntity is established by IfcPropertySetDdfinition; thus, the construction quality condition of IfcEntity can be expressed by the construction quality information contained in IfcProperty. In the IFC standard, the entity IfcBulidingElementType and its subtypes are used to describe the type of components. However, the predefined type classification in the IFC entities is too simple to cover the quality-related information which has been listed in quality standard for construction projects. Therefore, it is necessary to use the entity IfcPropertySet, which is a container class that holds dynamically extensible properties as a property set. The contained properties in the property set are described by using the entity IfcProperty which is the abstract supertype of the entities IfcSimpleProperty and IfcComplexProperty. IfcSimpleProperty is used to define a single property object, and its subtypes can be used to define various properties. IfcComplexProperty is used to define complex properties that may logically contain other properties. IfcProperty covers two subtype classes, IfcComplexProperty and IfcSimpleProperty, of which IfcSimpleProperty includes six subclasses. The contents in the elliptical dashed box in Figure 6 represent the quality properties defined previously, which are linked to PropertySet OnsiteReinforcedConcrete Beam/Column/Slab/Wall through thin full lines as explicit properties. The properties are assigned enumerated values or simple values that are connected to PropertySet by thin full lines.

Accordingly, an IFC-based quality evaluation information library was constructed to support building element compositions to be mapped to identify IFC objects such as IfcWall, IfcSlab, IfcBeam, and IfcColumn. In this study, the IFC model was proposed for integration with a quality-oriented database. Several external libraries, including structural elements and evaluation results, were loaded into the database as IfcLibrary and IfcPropertySet instances. The quality information collected from acceptance records and inspection files with calculation results in the BP neural network were used as data sources. In the expression process, the cast-in-place reinforced concrete elements were defined as property sets (IfcPropertySet) with inspection and evaluation records representing external product libraries (IfcLibrary). Seventeen properties such as concrete strength were defined as IfcSimpleProperty. The property values were defined by either IfcPropertyEnumeratedValue or IfcPropertySingleValue.

5. Integrated Database Construction for Construction Quality Evaluation

Data must be used accurately and effectively to enhance construction quality evaluation. If such data are integrated and visualized, then a reality-based virtual database environment can be constructed, which can then be used by an evaluation simulator and construction manager. Besides the quantitative information discussed above for mapping in the BIM model, the database should also include unstructured data, such as the BIM model (or drawings), site-quality documentations, and image and video records. These sources can be used to support visual display or auxiliary references for construction quality evaluation. To classify the structure of evaluation data reasonably, one must first identify the database composition according to the characteristics and functions of evaluation

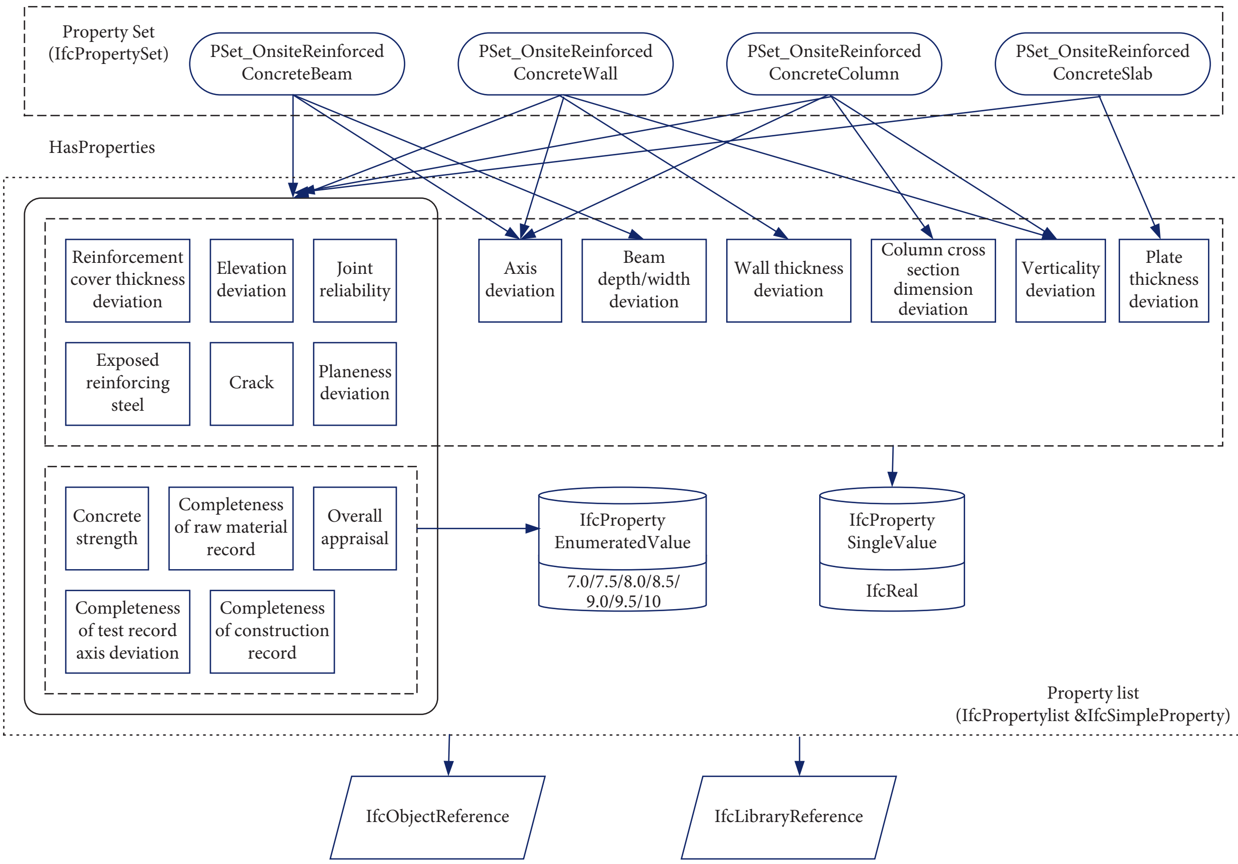


Figure 5: Instance model of IfcPropertySet

data. Three general categories were used in this study: (1) graphical evaluation data (i.e., the foundation of construction quality evaluation), normally obtained from views (or drawings) in the BIM model; (2) parametric evaluation data, which captures parameterized information with which the BIM model can reflect on the basic situation and quality status of a structure entity along with evaluation information that can be quantified in other construction quality record documents or described in a simple text format; and (3) other evaluation data involving raw materials certificates, on-site test records, construction quality acceptance records, contract documents, design documents, and related standard quality records as well as IFC documents, pictures, and video records, all of which provide reference material for construction quality evaluation.

5.1. Data Classification for Construction Quality Evaluation. Data classification is the process of organizing data into categories for effective and efficient use. With a complex composition and range of sources, the visual evaluation of construction quality consists of data with different storage structures. In Figure 7, graphical evaluation data are a type of unstructured data. Parametric evaluation data can be expressed via a two-dimensional logic relational table structure and extracted from attributes described in BIM models, which fall under structured data. Other evaluation data are usually classified to be graphical data and other data including pictures and audio and video form, belonging to unstructured data. These two kinds of data are integrated to support the evaluation results. Graphical evaluation data are a type of unstructured data. Parametric evaluation data can be expressed via a two-dimensional logic relational table structure, which falls under structured data. Other evaluation data are usually stored in documents, pictures, and audio and video form, belonging to unstructured data. According to the differences in storage structures for quality evaluation data, structured and unstructured data only apply; no semi-structured quality evaluation data exist (Figure 7).

5.2. Data Encoding for Construction Quality Evaluation. The approach to data encoding in this study relied on the process of converting quality-related data into a specific format using a given sequence of characters for convenient data storage and interpretation of the fractional project, constituent project, inspection lot, IFC element (i.e., structural element and evaluation indicator), and quality-related files, respectively.

5.2.1. Fractional Project and Constituent Project. Fractional project and constituent project information was encoded in the form of two letters. The first one is the entity title initial. For example, Fd represents *Foundation Engineering* and St represents *Structure Engineering* as shown in Table 9.

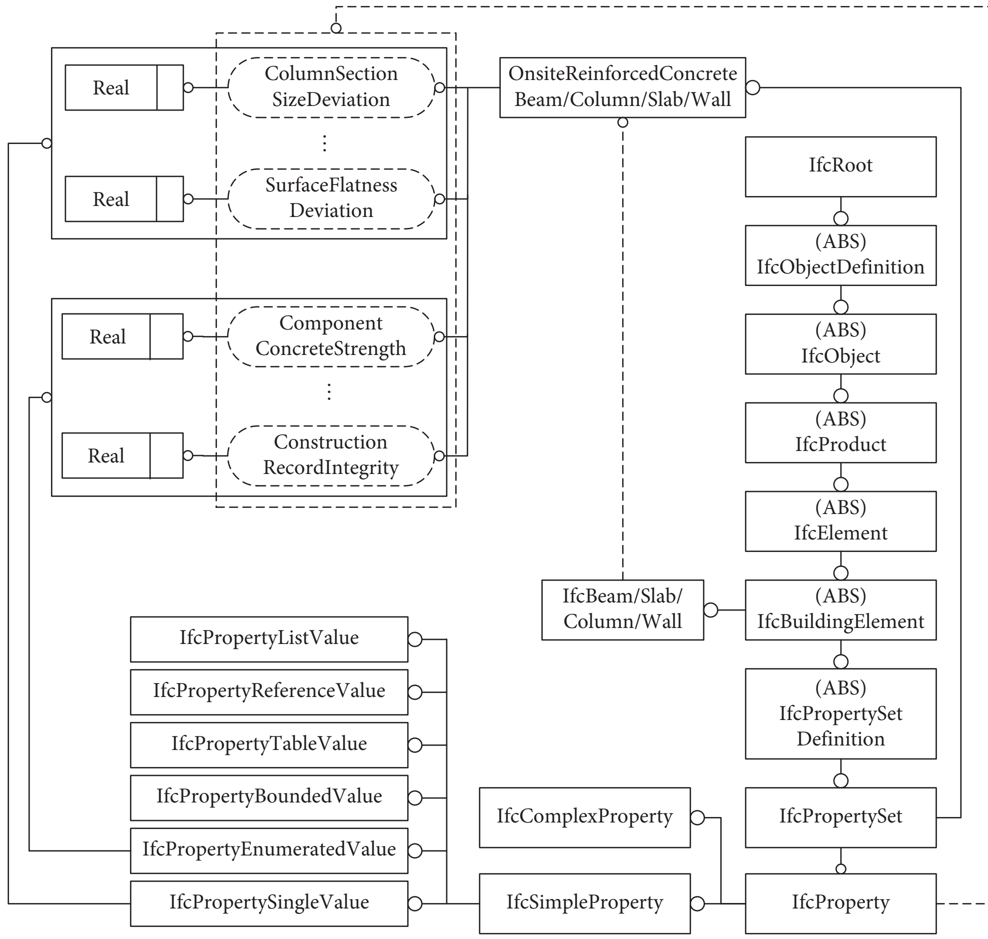


FIGURE 6: EXPRESS-G diagram for quality evaluation information.

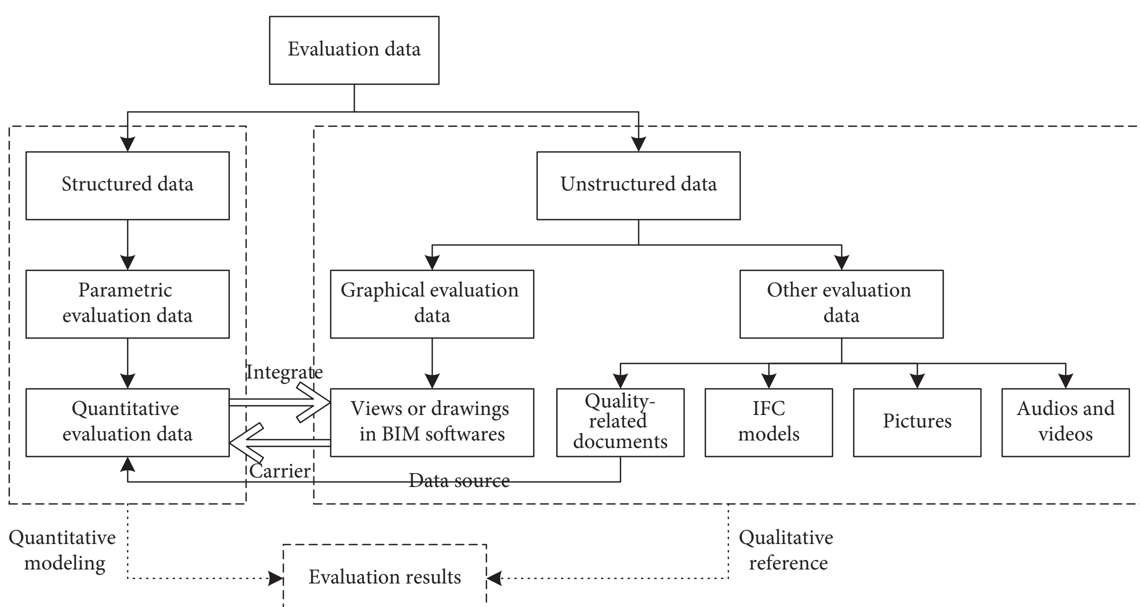


FIGURE 7: Data classification of quality evaluation.

5.2.2. Inspection Lot. Inspection lot information was encoded using 11 random letters and numbers in four sections connected by short lines. The first section is a four-digit number whose first two and last two numbers, respectively, represent the starting number and ending number of an inspection lot. The second section is a four-digit number whose first two and last two numbers, respectively, represent the starting number and ending number of the vertical axis of an inspection lot. The third section is a two-digit capital letter that represents the starting number and ending number of the horizontal axis of an inspection lot. The fourth section is a capital letter, representing either *beam*, *plate*, *column*, *wall*, or *all* by B, S, C, W, and A, respectively, according to the actual acceptance of an inspection lot; see Figure 8 for the encoding form.

5.2.3. IFC Element (Structural Element and Evaluation Indicator). During database construction, every IFC object is encoded with a name and description about the concepts, and a globally unique ID (GUID), that is, a 16-byte (i.e., 128-bit number) commonly split up into several fields of varying lengths and written in groups of hexadecimal characters. Per the IFC standard, *IfcGloballyUniqueId* as an attribute defined in entity *IfcRoot* holds an encoded string identifier that uniquely identifies an IFC object. To recognize different indicators attached to one IFC object, unique serial numbers must be assigned to evaluation indicators as well. This task involves a combination of five random letters and numbers in the form of two sections connected by short lines. The first section consists of three capital letters, organized by the initial letter of each attribute name in Table 10. The two-digit number in the second section is set as 01, 02, and 03 sequentially to identify the same evaluation indicators applied in different inspection lots as shown in Table 10.

5.2.4. Quality-Related Files. This step adopts a two-section form of six capital letters and numbers connected by short lines. The first section is a group number consisting of four letters or an alphanumeric code representing a file name extension, supplemented with the letter "X" if the code has fewer than four digits. The second section is a two-digit number used to distinguish files in the same format, numbered sequentially with 01, 02, and 03 as shown in Table 11.

5.3. Design for Conceptual Entity Model of Construction Quality Database. With regard to the visual requirements of construction quality evaluation and data characteristics in the database, entities and attributes are categorized into the following five entities: fractional project, constituent project, inspection lot, IFC element, and quality-related files. The first four consist of structured data about construction components and the quality acceptance workflow. Entity attributes of a quality-related file are considered unstructured data, mainly including graphical evaluation data and other types (Table 12).

After categorizing the entities and their corresponding attributes, it is important to consider the relationship between the entities and adopt a bottom-up strategy to designing the conceptual entity model in the quality database. The global entity-relationship (E-R) diagram is illustrated in Figure 9. The rectangle, ellipse, and diamond box, respectively, represent an entity, attribute, and relationship between entities in the diagram.

(1) One fractional project entity could be divided into a constituent project, denoted as a $1:n$ (one-to-many) relationship between these two entities; that is, one fractional project can be connected to multiple constituent projects whereas one constituent project belongs only to a specific fractional project.

(2) A constituent project entity and inspection lot entity are also connected in a $1:n$ relationship; that is, the evaluation of a constituent project requires inspection and testing of multiple inspection lots while every inspection lot is assigned to exactly one constituent project.

(3) One fractional project entity includes multiple IFC element entities represented as a $1:\mathrm{n}$ relationship; that is, one fractional project consists of multiple structural elements with corresponding property attributes from the IFC model while each structural element belongs to only one fractional project entity.

(4) An inspection lot entity and IFC element entity are connected in an $\mathrm{m}:\mathrm{n}$ relation: one inspection lot must be examined using multiple evaluation indicators while one evaluation indicator will be used and inspected for multiple inspection lots.

(5) A fractional project (or constituent project, inspection lot, IFC element) entity and related files entity are connected in a $1:\mathrm{n}$ or $\mathrm{m}:\mathrm{n}$ relationship; that is, the quality status of each fractional project (or constituent project, inspection lot, structural element, or evaluation indicator) is recorded in one or multiple quality files while each file can reflect the quality status of one fractional project (or multiple constituent project, inspection lot, structural element, or evaluation indicator).

5.4. Transforming Conceptual Data Model to SQL. When designing relational databases of construction quality evaluation, transforming the conceptual data model to candidate tables and their definitions in SQL requires a specific step. As illustrated in Figure 10, a major part of designing a relational database for construction quality involves dividing construction data elements and entities into related tables. In the process of construction quality management using this kind of quality information system, relationships between the tables are necessary to connect data in meaningful ways. The entities and relations in the E-R diagram in this study can be transformed into five relational tables (see Table 13, subtables 1, 2, 3, 4, and 10) comprising the fractional project, constituent project, inspection lot, IFC element, and quality-related files with

Table 9: Part of data encoding of fractional project.

Fractional project		Constituent project	
Name	Encoding	Name	Encoding
Ground foundation engineering	Fd	Reinforced constituent project	Rb
Structural engineering	St	Template constituent project	Tp
Decoration engineering	De	Concrete constituent project	Rc
Roofing project	Rf	Cast-in-place structure constituent project	Cs
Installation project	In		

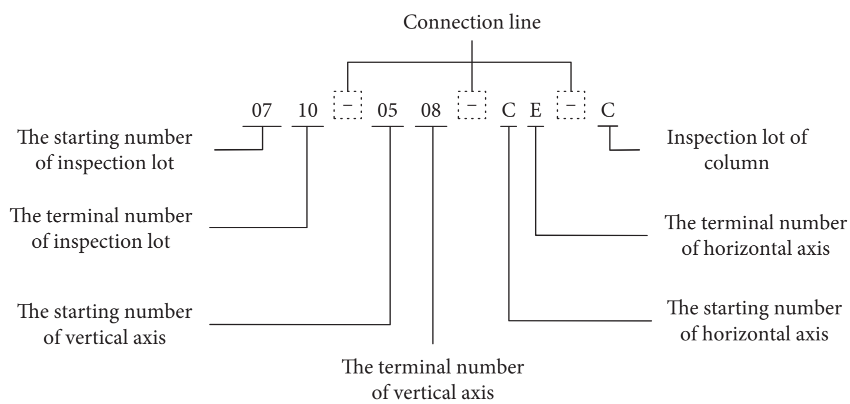


Figure 8: Example encoding of inspection lot of Column.

Table 10: Encoding of valuation indicator.

No.	Evaluation indicator name	Encoding	No.	Evaluation indicator name	Encoding
1	Concrete strength	CCS-01	10	Axis deviation	APD-01
2	Reinforcement cover thickness deviation	PLD-01	11	Elevation deviation	LED-01
3	Column cross section dimension deviation	CSD-01	12	Verticality deviation	LVD-01
4	Wall thickness deviation	WTD-01	13	Planeness deviation	SFD-01
5	Beam depth/width deviation	BHD-01	14	Crack	CXX-01
6	Plate thickness deviation	STD-01	15	Joint reliability	CRX-01
7	Completeness of raw material record	MRI-01	16	Exposed reinforcing steel	RBE-01
8	Completeness of construction record	CRI-01	17	Overall appraisal	SQS-01
9	Completeness of test record	TRI-01			

Table 11: Encoding of files.

File format	Encoding	File format	Encoding
PDF	PDFX-01	WAV	WAVX-01
DOC	DOCX-01	MP3	MP3X-01
PPT	PPTX-01	WMA	WMAX-01
TXT	TXTX-01	RMVB	RMVB-01
BMP	BMPX-01	MP4	MP4X-01
JPEG	JPEG-01	RFA	RFAX-01
JPG	JPGX-01	RVT	RVTX-01
GIF	GIFX-01	IFC	IFCX-01

associations that are either $m:n$ or $1:n$ on the "one" (i.e., parent) side. For example, fractional project entities stored in the information sheet shown in Figure 9 should be converted into a separate relational model with four attributes corresponding to the fractional project features. In subtable 1 of Table 13, the reference number of an entity is the primary key that can be uniquely identified to represent an individual row field in the table. Constituent project entities stored in an information sheet as shown in Figure 9 should be converted into a separate relational model with

Table 12: Classification of entities and attributes.

Entity	Attribute	Data source
Fractional project	Reference number	Table 9
	Name	Real name of specific fractional project
	Construction units	Contract document
	Construction quality score	Parameter information obtained from BIM models
Constituent project	Reference number	Table 9
	Name	Real name of specific constituent project
	Inspection result	Acceptance records for constituent quality
	Acceptance decisions	Acceptance records for constituent quality
	Professional technical director	Acceptance records for constituent quality
	Supervision engineer	Acceptance records for constituent quality
	Reference number of fractional project	Table 9
Inspection lot	Reference number	Figure 9
	Name	Real name of inspection lot
	Inspection data	Acceptance record for inspection lot quality
	Acceptance date	Acceptance record for inspection lot quality
	Construction standard and specification	Standards, specifications, design documents
	Inspection results of construction units	Acceptance record for inspection lot quality
	Acceptance decision of supervision unit	Acceptance record for inspection lot quality
	Reference number of inspection lot	Table 9
IFC element	Reference number of structural element	IfcGloballyUniqueId (entity IfcBuildingElement)
	Element name	IfcLabel (in entity IfcBuildingElement)
	Detailed description	IfcText (in entity IfcBuildingElement)
	Reference number of fractional project	Table 9
	Reference number of indicator	Table 1
	Indicator name	Indicator name in Table 1
	Evaluation standards and requirements	Standards, specifications, design documents
	Evaluation results	PSet_OnsiteReinforcedConcreteWall/Column/ Slab/Beam (in entity IfcWall as in Figure 6)
Quality-related files	Reference number	Table 11
	Name	File name
	Creation date	Time records of file creation
	Reference number of fractional project	Table 9
	Storage path	Storage position in system

seven attributes corresponding to the features of the constituent project. Meanwhile, by attaching a $1:n$ relation to this model, the reference number of the fractional project can also be viewed as an attribute reflecting the affiliative relationship between the fractional project and constituent project. The value of the reference number of the fractional project as a primary key in subtable 2 of Table 13 is considered a foreign key in the relational table of the constituent project.

The database system relies on matching values found in both tables to form relationships. In the relational table, an attribute can be designated as either a primary or foreign key. A primary key is used to uniquely identify a table or a row within a given table; a foreign key is a column that was formerly a primary key in a parent table that migrated to the child table and now identifies the relationship between the tables. The foreign key can participate as a key or non-key column within the child table. In subtable 10 of Table 13, the composite primary key refers to cases where more than one attribute is used to specify the primary key of the table. In such cases, GUID in IfcBuildingElement and the serial number of the evaluation indicators are used to uniquely identify a structural element with a particular evaluation. All foreign keys also include all attributes in the composite key, which can be different data types. For example, the foreign key of the *related_files* subtable, F_ComponentID and F_IndicatorID, references the composite primary key F_ComponentID and F_IndicatorID in the *IFC_element* subtable. During an insertion or update, if users try to insert a row into the *related_files* subtable whose values for F_ComponentID and F_IndicatorID do not correspond exactly to those of F_ComponentID and F_IndicatorID in an existing row in the *IFC_element* subtable, the database server will return an error.

Two basic relationships emerged when modeling the database: identifying (i.e., mandatory) and nonidentifying (i.e., optional). When both entities are mandatory, each entity becomes a table, and the key of either entity can appear in the other entity's table as a foreign key. One of the entities in an optional relationship should contain the foreign key of the other entity in its transformed table. When both entities are optional, either entity can contain the embedded foreign key of the other entity, with nulls allowed in the foreign keys. The $1:n$ relationship can appear as either mandatory or optional on the "many" side without affecting the transformation. On the "one" side, the relationship may be either mandatory ((a) in Table 14) or optional ((b) in Table 14). In all cases, the foreign key must appear on the "many" side, representing the child entity, with nulls allowed

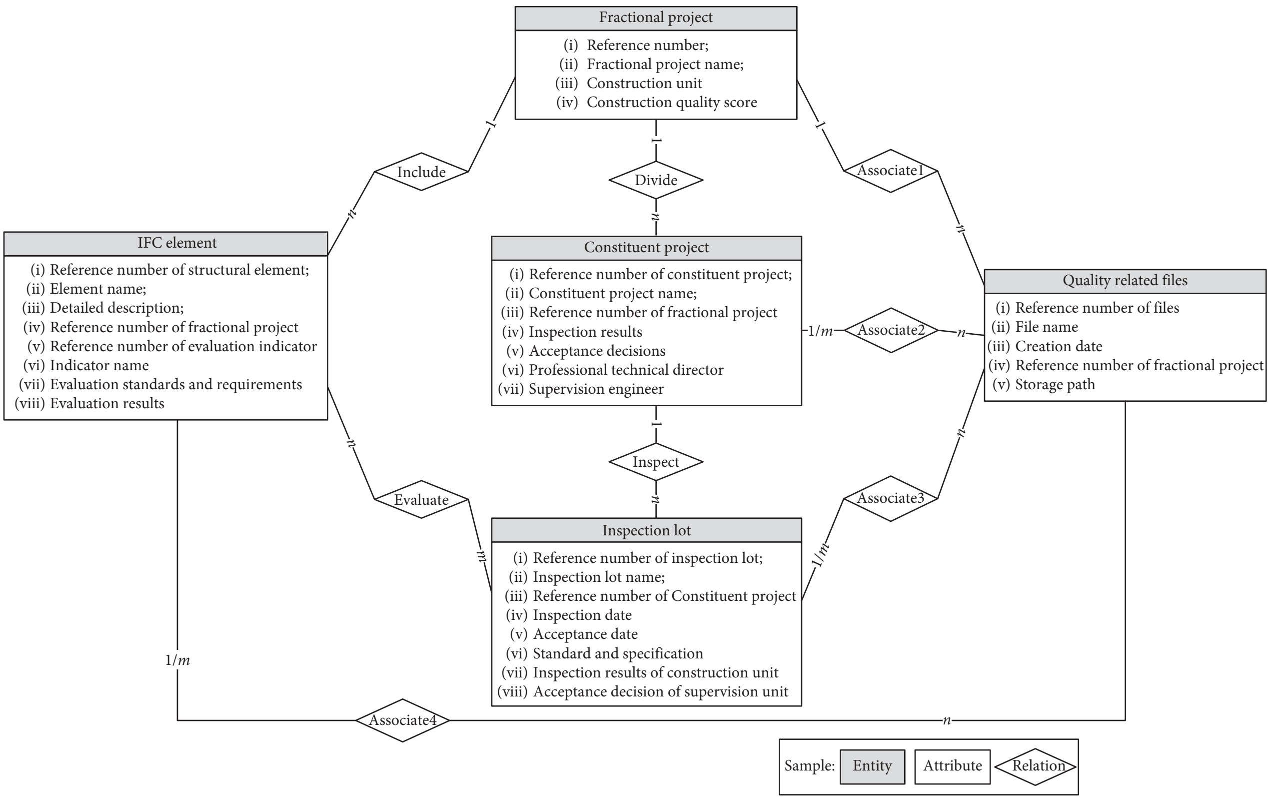


Figure 9: The workflow of quality database operation.

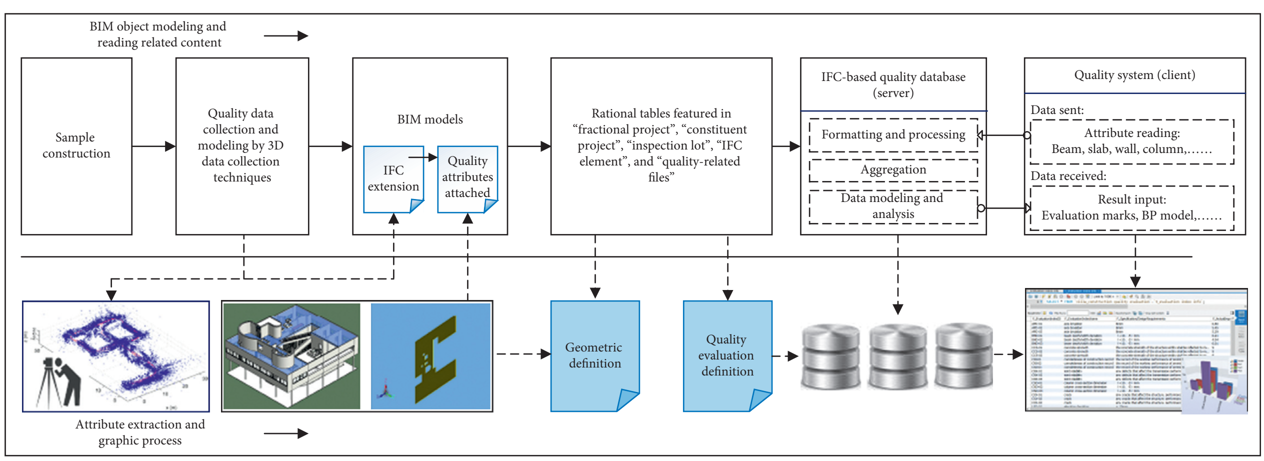


Figure 10: E-R diagram for quality evaluation database.

for foreign keys only in the optional "one" case. Foreign key constraints are set according to the specific meaning of the relationship and may vary from one relationship to another. The $m:n$ relationship, depicted in (c) and (d) in Table 14 as optional and mandatory for both entities, requires a new table containing the primary keys of both entities. The same transformation applies to either the optional or mandatory case, including that the "not null" clause must appear for the foreign keys in both cases. An optional entity means that the corresponding SQL table derived may have zero rows for that particular relationship, which would have no effect on "null" or "not null" in the table definition.

6. Operating the IFC-Based Database

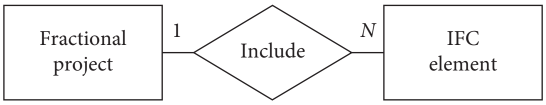
6.1. Workflow of the Proposed Method. Considering the complexity of large construction projects, it is crucial to establish a construction quality management system that

Table 13: Relational tables of the database.

Relational tables			
Name	Attribute	Data type	Constraint
Subtable 1—fractional project			
F_BranchWorkID	Reference number	Char(2)	Primary key
F_BranchWorkName	Name	Varchar(12)	Required
F_ConstructionU	Construction units	Varchar(40)	Required
F_ConstructureQS	Construction quality score	Decimal(4,2)	Required
Subtable 2—constituent project			
F_ConstituentPID	Reference number	Char(2)	Primary key
F_ConstituentPName	Name	Varchar(12)	Required
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ConstituentPIR	Inspection result	Varchar(100)	Optional
F_ConstituentPAD	Acceptance decisions	Varchar(100)	Required
F_ConstituentPTD	Professional technical director	Varchar(10)	Required
F_ConstituentPSE	Supervision engineer	Varchar(10)	Required
Subtable 3—inspection lot			
F_InspectionLotID	Reference number	Char (14)	Primary key
F_InspectionLotName	Name	Varchar(50)	Required
F_ConstituentPID	Reference number	Char(2)	Foreign key
F_InspectionLotDate	Inspection date	Date()	Required
F_InspectionLotAD	Acceptance date	Date()	Optional
F_InspectionLotS	Construction standard and specification	Varchar(50)	Required
F_InspectionLotIR	Inspection results of construction units	Varchar(100)	Required
F_InspectionLot SU	Acceptance decision from supervision unit	Varchar(100)	Required
Subtable 4–files			
F_DocumentID	Reference number	Char(7)	Primary key
F_DocumentName	File names	Varchar(40)	Required
F_CreateTime	Creation date	Date()	Optional
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_StoragePath	Storage path	Varchar(40)	Required
Subtable 5—evaluate			
F_InspectionLotID	Reference number	Char (14)	Foreign key
F_ComponentID	Reference number of element	Varchar(100)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6))	Foreign key
Subtable 6—include			
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ComponentID	Reference number of element	Varchar(100)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6))	Foreign key
Subtable 7—divide			
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ConstituentPID	Reference number	Char(2)	Foreign key
Subtable 8—associate			
F_DocumentID	Reference number	Char(7)	Primary key
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_ConstituentPID	Reference number	Char(2)	Foreign key
F_InspectionLotID	Reference number	Char (14)	Foreign key
F_ComponentID	Reference number of element	Varchar(100)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6))	Foreign key
Subtable 9—inspect			
F_ConstituentPID	Reference number	Char(2)	Foreign key
F_InspectionLotID	Reference number	Char (14)	Foreign key
Subtable 10—IFC element			
F_ComponentID	Reference number/GUID in IfcBuildingElement	Varchar(100)	Composite key
F_ComponentName	Ifc element name	Varchar(20)	Required
F_ComponentDetail	Detailed description	Varchar(20)	Required
F_BranchWorkID	Reference number	Char(2)	Foreign key
F_IndicatorID	Reference number of evaluation indicator	Char(6)	Composite key
F_IndicatorName	Indicator name	Varchar(20)	Required
F_EvaluationSR	Evaluation standards and requirements	Varchar(200)	Required
F_EvaluationResult	IfcPropertySet on Wall/Column/Slab/Beam	Varchar(5)	Required

Table 14: Relationship between two entities.

(a) $1:n$, both entities mandatory



Every structural element belongs to exactly one fractional project, and each fractional project has at least one structural element

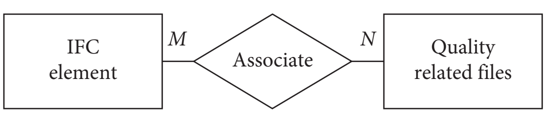
```
Create table fractionalproject
    (F_BranchWorkID char(2),
    F_BranchWorkName varchar(12),
    F_ConstructionU varchar(40),
    F_ConstructureQS decimal(4,2),
    Primary key (F_BranchWorkID));
Create table IFCelement
    (F_ComponentID Varchar(100),
    F_ComponentName varchar(20),
    F_ComponentDetail varchar(20),
    F_BranchWorkID char(2) not null,
    F_IndicatorID Char(6),
    F_IndicatorName varchar(20),
    F_EvaluationSR varchar(200),
    F_EvaluationResult varchar(5),
    Primary key (F_ComponentID, F_IndicatorID);
    Foreign key ((F_BranchWorkID) references
fractionalproject
    On delete set default on update cascade),
```

(b) $1:n$, one entity mandatory, one entity optional

Each fractional project is evaluated in one or more related file. A given quality-related file may not necessarily belong to a fractional project

```
Create table fractionalproject
    (F_BranchWorkID char(2),
    F_BranchWorkName varchar(12),
    F_ConstructionU varchar(40),
    F_ConstructureQS decimal(4,2),
    Primary key (F_BranchWorkID));
Create table relatedfiles
    (F_DocumentID char(7),
    F_DocumentName varchar(40),
    F_CreateTime date(),
    F_BranchWorkID char(2),
    F_StoragePath varchar(40),
    Primary key (F_DocumentID),
    Foreign key (F_BranchWorkID) references fractionalproject
    On delete set default on update cascade);
```

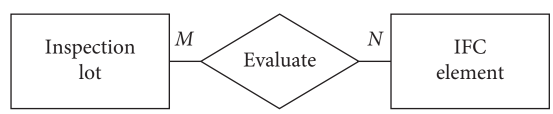
(c) $m:n$, one entity mandatory, one entity optional



Each evaluation property attached in IFC elements is applied in one or more quality-related files. A given quality-related file may not necessarily include a structural element with quality attributes

```
Create table IFCelement
    (F_ComponentID Varchar(100),
    F_ComponentName varchar(20),
    F_ComponentDetail varchar(20),
    F_BranchWorkID char(2),
    F_IndicatorID Char(6),
    F_IndicatorName varchar(20),
    F_EvaluationSR varchar(200),
    F_EvaluationResult varchar(5),
    Primary key (F_ComponentID, F_IndicatorID);
Create table relatedfiles
    (F_DocumentID char(7),
    F_DocumentName varchar(40),
    F_CreateTime date(),
    F_BranchWorkID char(2),
    F_StoragePath varchar(40),
    Primary key (F_DocumentID),
Create table associate4
    (F_DocumentID char(7),
    F_ComponentID Varchar(100),
    F_IndicatorID Char(6),
    Primary key (F_DocumentID, F_ComponentID,
F_IndicatorID);
```

(d) $m:n$, both entities mandatory



Each structural element is evaluated in one or more inspection lot. And one inspection lot consists of one or more structural elements

```
Create table Inpectionlot
    (F_InspectionLotID char(14),
    F_InspectionLotName varchar(20),
    F_ConstituentPID char(2),
    F_InspectionLotDate date(),
    F_InspectionLotAD date(),
    F_InspectionLotS varchar(50),
    F_InspectionLotIR varchar(100),
    F_InspectionLot SU varchar(100),
    Primary key (F_InspectionLotID);
Create table IFCelement
    (F_ComponentID Varchar(100),
    F_ComponentName varchar(20),
    F_ComponentDetail varchar(20),
    F_BranchWorkID char(2),
    F_IndicatorID Char(6),
    F_IndicatorName varchar(20),
    F_EvaluationSR varchar(200),
    F_EvaluationResult varchar(5),
    Primary key (F_ComponentID, F_IndicatorID);
Create table evaluate
    (F_ComponentID Varchar(100) not null,
    F_IndicatorID Char(6),
```

Table 14: Continued.

Foreign key (F_DocumentID) references **relatedfiles** on delete set default on update cascade),	F_InspectionLotID char(14),
	Primary key (F_InspectionLotID, F_ComponentID, F_IndicatorID),
Foreign key (F_ComponentID, F_IndicatorID) references **IFCelement**(F_ComponentID, F_IndicatorID) on delete set default on update cascade);	Foreign key (F_InspectionLotID) references **Inspectionlot** on delete set default on update cascade), Foreign key (F_ComponentID, F_IndicatorID) references **IFCelement** (F_ComponentID, F_IndicatorID) on delete set default on update cascade);

acts as distributed data storage for BIM data. Like other BIM applications, the IFC-based construction quality management system tends to be influenced by project organizational structure, working relationships, or even social networks, all of which are influenced by a specific evaluation database. Quality database operations cannot be disconnected from the model with which construction information is organized and illustrated according to a standard like IFC. As shown in Figure 9, the prototypical framework was developed based on an IFC extension and mathematical method (i.e., neural network model) for predicting overall appraisal, whereby indicator selection and database table design are normally organized sequentially. In the workflow, the quality data of structural elements are collected to compute the value of quality content, and it is important to establish an evaluation indicator system that accounts for performance testing, quality records, allowable deviation, and appearance quality. Then, the evaluation information is aligned with open international standards of IFC according to which the BP neural network model can be trained and tested as expected, and then the approved model can be used to predict the construction quality score. A formalization structure is suggested for database tables to facilitate the exchange of IFC-based evaluation indicator information via the information provider and information receiver, which maintains the information exchange between the IFC model and database tables. With regard to the visual requirements of construction quality evaluation and data characteristics in the database, entities and attributes of structural elements are categorized into the following five database tables as quality information server: fractional project, constituent project, inspection lot, IFC element, and quality-related files. Lastly, to design the relational databases of quality evaluation system as the information client, the conceptual data model is transformed and defined in SQL.

Ideally, several 3D data collection techniques including scanning, photogrammetry, virtual modeling, 3D printing, and rapid prototyping can be employed to capture quality information about construction projects. In the design stage, the IFC extension is developed to synthesize various evaluation modes and derives an optimal expression in a geometric and evaluation definition, thus constructing an entire BIM to be shared with the database as a server. Furthermore, MySQL Workbench as client is suggested to extract attributes from the database server and to migrate complex database systems. According to the logic structure design described above, relevant evaluation data were obtained and then imported directly into the corresponding field manually to create the database tables (Figure 11) and realize the preliminary establishment of a construction quality evaluation database. Users can access the quality database as a server through data sent by the quality system client, which is also fed back to the evaluation results stored in the IFC model.

6.2. Implementation of the Case. The proposed IFC-based quality database of this paper was applied to the case study of cast-in-place steel-concrete structure which is evaluated by 16 quality indicators in four categories (i.e., performance testing, quality records, allowable deviation, and appearance quality). When the inspection request for "cast-in-place steel-concrete" structural elements (beam, slab, column, and wall) was confirmed; the corresponding quality evaluation template and predicted results from BP network were identified based on inspection data collection and structured data from BIM model. The professional quality inspector completes the checklist with construction information and inspection data obtained from the construction site. Any data with a deviation beyond tolerated variance will be identified and recorded in the relevant attributes of the BIM model. Then, an acceptance rate for each evaluation indicator will be generated in the IFC-based quality database developed in SQL. Lastly, the overall quality appraisal of the case of cast-in-place steel-concrete structure is rated as "Good". According to the average value of each evaluation indicator, in terms of performance testing, quality records, allowable deviation, and appearance quality, and the construction quality of the four aspects remained equivalent and demonstrated no significant differences. From these four aspects, the concrete strength in the testing project was found to be relatively superior while the wall thickness deviation was somewhat large.

Therefore, the following points for further improvement in follow-up construction warrant attention. First, the technology and attitude of construction personnel and quality of construction equipment should be improved. Second, records of raw materials in quality records should be complete, true, and valid, and procedures should be complete and well documented. Third, testing records and construction records must be enhanced. Fourth, the construction quality status reflected by each indicator in terms of allowable deviation should align with that of appearance quality. Finally, the quality of template installation and cleanliness of the internal surface should be strictly controlled to reduce size deviation and improve appearance quality.

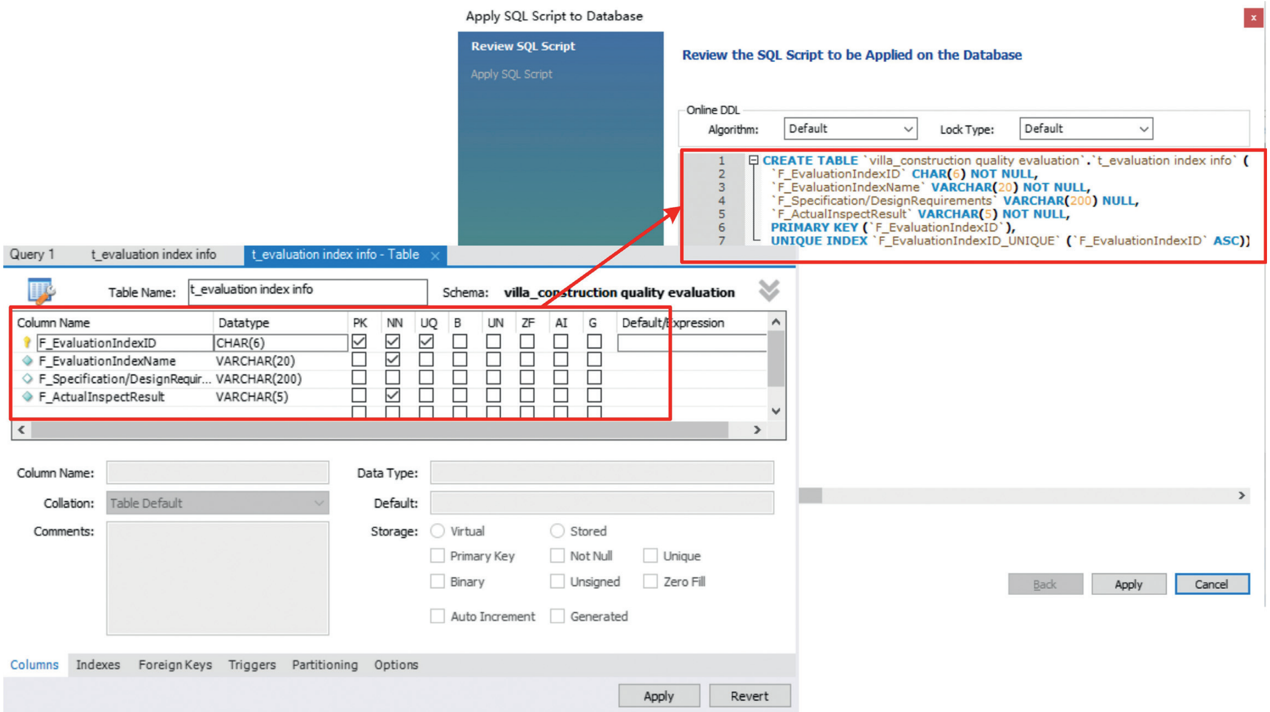


Figure 11: Create a new evaluation index information table.

Based on the discussion above, the IFC standard can be used to describe construction quality information as a whole. However, the current version of the IFC standard could not yet directly support the expression of the construction quality evaluation. Therefore, it needs to be extended in order to support the direct data exchange with the relevant quality database. The BIM model for quality evaluation established in this paper is used to realize the logical association among structural elements, evaluation items, quality indicators, and attribute sets. The research not only lays a sound foundation for developing the BIM-based application software for construction quality evaluation but also shows a feasible approach to extending the IFC standard to satisfy the requirements for quality management.

7. Evaluation of Proposed Method

The objective of evaluating the proposed model is to understand the effectiveness of IFC-based database if implemented in real practice. In order to take the opinion of construction firm and design institutes about identified factors, a questionnaire was developed. To make questionnaire simple and easy to understand, it was divided into three sections. The first section represents the composition of respondents. The second section includes statistical graphs of the means of survey results and the categorical weights of survey factors. In the third section, weights were assigned by respondents to factors in relation to quality for interpretation of data. Weights are in the range of 1 to 10. Zero to two is in poor range, two to four is in fair range, four to six is in average range, six to eight is in good range, and eight to ten is excellent range.

The survey was conducted by distributing a developed questionnaire to different construction practitioners. A total of 117 construction professionals including construction managers and structural designers participated in the survey. In this study, surveys were used to evaluate the four primary objectives of proposed method: (1) to increase the ability of construction managers to use BIM technology for quality control; (2) to involve structural designers in parametric-oriented quality control activities including the use of BIM software; (3) to expose key quality information to model builders and users; and (4) to provide complete quality database to develop management platform as well as information storage system. The results of the survey filled out by 64 participants in construction management and 19 participants in structural design are summarized in Table 15.

There are several points of note in the table. BIM technology and related data are considered very effective in increasing participants' awareness in design and management process (means across both groups reached 6.77 out of 10 in "Good" and 5.98 close to "Good"), benefiting users with the integration, utilization, and visualization of construction quality information related to IFC model (means across survey results fell in "Good"). This is also revealed that survey participants saw significant value of IFC-based quality database which could offer them an advantage in their work. However, the IFC-based method was not as enough effective in improving work efficiency both for construction managers and structural designers (both means were located in "Average" level). Actually BIM helps not just in constructing "buildings" but also in building a new sort of quality management mode. It is an integrated process built on coordinated and reliable information about a project

Table 15: Evaluation of the proposed method.

Evaluation questions	Participant		Mean	Poor (0~2)	Fair (2~4)	Average (4~6)	Good (6~8)	Excellent (8~10)
1. How familiar were you with BIM?	Construction Manager ($n = 64$)		6.77	0	0	19	33	12
	Structural designer ($n = 53$)		5.98	0	2	27	19	5
2. To what extent can IFC-based quality database improve information integration of construction quality?	Construction Manager ($n = 64$)		7.55	0	0	17	37	10
	Structural designer ($n = 53$)		6.99	0	0	31	18	4
3. To what extent can IFC-based quality database improve information utilization of construction quality?	Construction Manager ($n = 64$)		7.27	0	1	15	22	26
	Structural designer ($n = 53$)		6.5	0	0	20	25	8
4. To what extent can IFC-based quality database improve the visualization of quality management?	Construction Manager ($n = 64$)		7.73	0	0	7	21	36
	Structural designer ($n = 53$)		7.18	0	0	13	20	20
5. To what extent can IFC-based quality database improve work efficiency of quality management?	Construction Manager ($n = 64$)		5.34	0	12	29	20	3
	Structural designer ($n = 53$)		5.02	0	15	20	18	0
6. To what extent can IFC-based quality database improve understanding of construction quality control?	Construction Manager ($n = 64$)		6.82	0	0	21	24	19
	Structural designer ($n = 53$)		6.12	0	5	17	21	10
7. How useful do you consider the overall method proposed?	Construction Manager ($n = 64$)		5.88	0	7	22	30	5
	Structural designer ($n = 53$)		5.01	0	6	16	28	3

from design through construction which give users more time to adapt it. Another question worthy of deep conversation on quality control reveals that this may be due in large part that the primary reason why participants would like to use IFC-based database was because BIM can be considered a thought process that improves the understanding of construction quality through various stages of the project in the shape of information that stays digital, consistent, and coordinated; for example, a large part of participants' responses to the survey indicated this was one of the primary reasons (means of the two groups reached "Good" level), while more than 50% of these participants stated that they think highly of the effect of the overall method utilized in quality evaluation.

8. Conclusion

The presented findings contribute to the understanding of the potential use of BIM in construction quality evaluation and fill an existing gap in data integration on the use of relational database. This paper explored the implementation of BIM in quality management and proposed integrated solutions to improve current quality management processes with assistance of an IFC-based working environment. In order to better utilize the performance of the BIM model and database on construction quality control, a variety of BIM-based evaluation frameworks have been proposed. Also, this paper discusses how these IFC and neutral network models will work together to facilitate construction quality management. It helps the project participants to better understand the quality progress and to collaborate more effectively, thanks to a visualized data format.

In this way, the IFC-based construction quality model is effective and reliable for participants to understand quality problems and track the corrective action. The benefits of the construction quality database proposed in this paper lie in the aspects as follows: first, the utilization of the IFC data mapping in construction quality domains ensures information consistency and predicated results. Furthermore, the quality data and structured construction codes are integrated to provide clear quality definition requirements for evaluation. Typical errors caused by misunderstanding of cross-reference codes can be avoided. Lastly, IFC-based quality database ensures a source of information for quality management techniques to identify useful evaluation attributes in data to inform users, which helps the project participants to better understand the quality requirements acceptance and to collaborate in a visualized manner.

It can be concluded that BIM and database technology-integrated construction quality evaluation method is suitable and helpful in quality compliance management. A quality system based on this approach proposed in this study could allow us to automate data acquirement and extraction from the BIM model and produce evaluation information that can also be used by users of the quality system platform. Whilst there is a significant amount of time for us to implement the mapping of the IFC element against evaluation results, the benefits to users are they do not need to manually seek corresponding data which are attached to a BIM model as a database. The effort invested to create the mapping will allow us to ultimately move to being able to produce reliable IFC-based quality database. Like any new feature, there is always room for improvement, the requirement of more automation, and new functionality generated with the development of quality system platform is a giant step towards massive open-structured and unstructured data-related construction quality.

There are some limitations for the proposed method as follows: (1) the IFC extension model designed for quality evaluation does not contain unstructured data related to construction quality, such as outward appearance and historical inspection records. Therefore, unstructured data should be considered in the quality-oriented BIM model. (2) The use of IFC-based database is not convenient and automatic at this time with the proposed method due to the manual input of the evaluation results. Related evaluation software application should be developed in the future for improvement in recording field data and direct data transfer to BIM.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Related work on this study has been presented in the International Conference on Construction Engineering and Project Management 2017

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Political Risk Paths in International Construction Projects: Case Study from Chinese Construction Enterprises

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International construction enterprises (ICEs) have been plagued with political risks in the global market. To ensure the success of political risk management, it is necessary to comprehend the political risks in international construction projects. This study aims at exploring the political risk paths in international construction projects. The preliminary political risk factors and paths were proposed from the literature review. A survey questionnaire was developed to collect political risk cases faced by Chinese construction enterprises (CCEs) performing international construction projects, and 264 valid cases were received and analyzed for this study. Adopting the confirmatory factor analysis (CFA) method, 6 macrofactors ("sociopolitical stability" (A), "legal and regulatory" (B), "social safety" (C), "economy performance" (D), "attitude towards foreigners" (E), and "international environment" (F)) and 2 microfactors ("low exposure" (G) and "capability of enterprises" (H)) were identified. Moreover, the results of path analysis illustrated that 7 factors (A, B, C, D, E, G, and H) had the significant direct negative effect on "risk consequences" and 3 factors (A, D, and F) had the indirect negative effect on "risk consequences." The findings from this study help practitioners gain an in-depth understanding of political risks in international construction projects and provide a useful reference for ICEs to manage political risks when venturing outside their home countries.

1. Introduction

As China joined World Trade Organization (WTO) and the local construction market has reached the saturation point, many well-known Chinese construction enterprises (CCEs) began to carry out construction works in overseas projects [1]. According to the data of Engineering News-Record (ENR), the revenues of Chinese contractors increased from $8.8 billion in 2004 to $98.7 billion in 2016, with the first ranking in the world, and 65 Chinese contractors were included in the ENR's top 250. With the proposition of Silk Road Economic Belt strategy, more and more CCEs will step abroad to expand their market worldwide [2].

However, despite the tremendous opportunities, CCEs have also witnessed a dramatic increase in political risks around the world, particularly in developing countries [3]. In 2015, three executives of the China Railway Construction Corporation were killed in the Mali terrorist attack. In 2014, the Mexican government annulled a business deal with a Chinese-led consortium over its first high-speed railway project due to public concerns about the bidding process. In 2012, in the armed conflict between Sudanese rebels and the local government, 29 Sinohydro staff members in a highway project were kidnapped by Sudanese rebels. Political risks have brought huge losses to CCEs and will be a persistent obstacle to the development of the Chinese overseas construction business.

With consideration of the negative and significant impact of political risks on international construction projects, how to effectively manage political risks has become a hot issue for international construction business [4]. The participants of international construction projects come from different countries with different values, religions, habits, customs, and codes of conduct. Compared to domestic construction projects, international construction projects are more vulnerable to political risks [5]. Successful political risk management is inseparable from a thorough understanding of political risks. International construction enterprises (ICEs) should fundamentally master the knowledge of political risk management before marching into the overseas market [3, 6]. Political risk is the result of the interaction of a series of driving factors [7]. To achieve success in political risk management practices, it is necessary for ICEs to identify these factors and their interrelationships.

It should be noted that the political risks ICEs confronted in the global market are obviously different from that of traditional multinational enterprises. Exporting goods and services are the main business of ICEs. Due to the lack of capital investment, ICEs do not have the exposures that arising from establishment and maintenance of a production facility [8]. Moreover, ICEs are not resource-based enterprises, so they rarely encounter conflicts with local governments and organizations who are concerned with natural resources [5]. In most cases, international construction business is project-specific. ICEs are concerned primarily with the stability of their expected returns in a short time period. Therefore, they are extremely sensitive to environmental fluctuations that can severely influence project cash flow.

Nonetheless, the existing literature mainly focused on the political risks arising from international general business (e.g., foreign direct investment, trade in goods, and international joint ventures) of traditional multinational enterprises and paid less attention on the political risks residing in international construction business. Since international construction business and international general business have different political risks [5], the theory of political risk associated with the international general business maybe not completely appropriate to the international construction business. As a result, the specific objectives of this study are (1) to identify the political risk paths in international construction projects and (2) to examine the significance of those risk paths.

As less attention has been paid to political risk management in the international construction business, this study can contribute to the existing body of knowledge. Furthermore, when ICEs venture outside their home countries, the findings from this study can assist ICEs by providing a reference in clearly understanding the political risk arising from the international construction business as well as their relative relationships represented by risk paths.

2. Background

The definitions of political risk can be mainly split into two groups [4, 9]. The first approach emphasized the causes of political risk while regarded political risk as the possibility of the adverse consequences produced by political events (e.g., wars, regime changes, revolutions, political violence, riots, insurrections, terrorist attacks, and coups) and government activities (e.g., expropriations, unfair compensations, foreign exchange restrictions, illegal interferences, changes in laws, corruption, poor enforcement of the contract, and labor restrictions) [10, 11]. The second approach focused on the consequences of political risk and defined political risk as negative impacts on enterprises due to the deterioration of political environment [12, 13]. Combining the two aforementioned approaches, political risk in international construction projects can be defined as the uncertainty of political events and arbitrary or discriminatory actions by host governments or political groups that might have adverse effects on the objectives of ICEs.

Risk factors can be defined as variables influencing risk increase or decrease [14]. Some studies identified a list of political risk factors. For example, Jakobsen maintained that obsolescing bargain mechanism, sociopolitical instability and grievances, political institutions, and preferences and attitudes are the main political risk factors in international business [15]. Tsai and Su established a political risk assessment model for port projects and grouped political risk factors into five categories: project development policy, project management policy, foreign enterprise policy, political and social systems, and macroeconomic practices [16]. Moreover, some studies have examined political risk factors in international construction projects. For example, Deng and Low identified the political risks in international construction projects and categorized 85 political risk factors into five levels: international environment, host country, industry-specific, project-specific, and firm-specific [7]. Deng et al. stated that political risk in international projects bursts when external threats and internal vulnerability overlap and concluded that the internal vulnerability of project systems are determined by the characteristics of projects and firms [17]. These studies shared a common shortcoming that they overlooked the causal relationships among political factors and consequences.

In this study, a total of 29 political risk factors and 3 political risk consequences were identified from a comprehensive review of the relevant literature. To verify the comprehensiveness of the identified risk factors and consequences, a pilot survey was performed with a few experts to collect their opinions on the preliminary list of the risk factors and consequences. These experts were (1) five Chinese professors who focused on international project management and political risk management and (2) five senior managers who came from five CCEs (China Communications Construction Group Limited, Power Construction Corporation of China, China State Construction Engineering Corporation, and China Railway Group Limited). All of the 10 experts had more than 20 years of work experience. Based on the pilot survey, the 29 political risk factors and 3 political risk consequences were divided into nine groups (i.e., Groups A to I) (Table 1): "sociopolitical stability" (A1–A3), "legal and regulatory" (B1–B5), "social safety" (C1–C5), "economy performance" (D1–D4), "attitude towards foreigners" (E1–E3), "international interactive relations" (F1–F3), "low exposure" (G1–G3), "capability of enterprises" (H1–H3), and "risk consequences" (I1–I3).

Some studies have discussed the relationships among political risk factors. For example, Annett deemed that government instability can result in poor legislation and regulation and thereby increase the political risk [18]. Rice and Mahmoud argued that economy performance of the host country has strong relationships with sociopolitical stability and public safety [29]. Yaprak and Sheldon believed that international environment can affect the host country's

Table 1: Political risk factors and consequences in international construction projects.

Grouping	Factors	References
A: sociopolitical stability	A1: government unity	[7, 18, 19]
	A2: factional conflicts	[7, 18, 19]
	A3: religious and ethnic tensions	[7, 18, 19]
B: legal and regulatory	B1: poor enforcement mechanisms	[7, 20, 21]
	B2: policy uncertainty	[4, 5, 21]
	B3: unfairness of judicial process	[7, 20, 22]
	B4: price controls	[4, 5]
	B5: speediness of judicial process	[7, 20]
C: social safety	C1: crime	[4, 23]
	C2: terrorism	[4, 23]
	C3: violent demonstrations	[4, 23]
	C4: armed conflicts	[4, 23]
	C5: kidnapping or extortion	[4, 23]
D: economy performance	D1: inflation	[5, 24, 25]
	D2: unemployment	[5, 24, 25]
	D3: exchange rate volatility	[5, 24, 25]
	D4: recession	[24–26]
E: attitude towards foreigners	E1: hostility to foreigners	[5]
	E2: confiscation or expropriation	[26]
	E3: discrimination against foreign companies	[5, 27]
F: international interactive relations	F1: external conflicts	[3, 9]
	F2: international economic crisis	[3, 9, 26]
	F3: external interferences	[3, 9, 28]
G: low exposure	G1: low attribute exposure	[17]
	G2: low strategy exposure	[17]
	G3: low transaction exposure	[17]
H: capability of enterprises	H1: core competitive capacity	[17]
	H2: relative bargain capacity	[17]
	H3: integrate adaptive capacity	[17]
I: risk consequences	I1: profits	[5, 7]
	I2: stability and sustainability	[5, 7]
	I3: safety	[5, 7]

politics, law, economy, and security. However, these studies mainly focused on the political risks in international general business [30]. The relationships among the political risk factors and consequences have not been examined in the context of international construction projects. After a comprehensive literature review, 18 hypothesized political risk paths in international construction projects were proposed (Figure 1), which will be tested in this study.

3. Research Methods

3.1. Date Collection. To verify whether the 18 proposed political risk paths are significant in international construction projects, a structured questionnaire was developed to collect the political risk cases from CCEs performing international construction projects. The questionnaires were composed of three parts: (1) the basic data of respondents (firm, work experience, title, and location); (2) the data related to the characteristics of the respondents' firms and projects they participated in G1–G3 and H1–H3; and (3) the data associated with the political risk cases (risk events, date, and I1–I3).

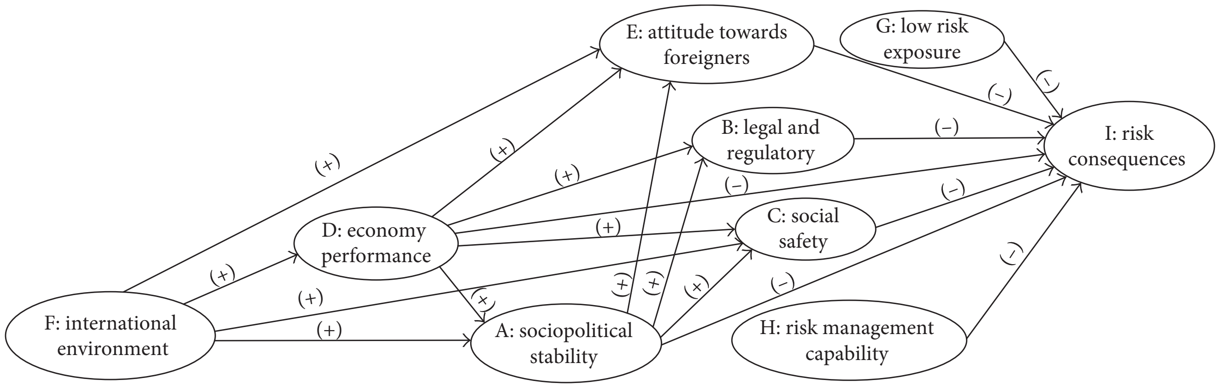
According to the previous study, the aforementioned factors can be measured by a list of observed indicators [17]. To avoid ambiguity and ensure respondents have accuracy in replying to questions, the brief introduction of political risk and the quantitative standard of each indicator were also attached to the questionnaire. For example, the score of "low attribute exposure" (G1) equals to the weighted average score of 5 items: "public opposition to the project," "project size," "prioritized of the project location," "technical and managerial complexity of the project," and "misconduct of contractors." All the items were measured in a relative way. For instance, the contract amount was a proxy of "project size," which was positively correlated with the political risk level. The projects with different contract amount were given the scores from 1 to 5, where 5 = the largest contract amount and 1 = the smallest contract amount.

To collect political risk cases, all the Chinese practitioners who have experience in overseas construction business were considered as the target of the survey. By reviewing the websites, reports and publications of CCEs, economic counsellor's office of the Chinese Embassy, Chinese construction management research sector, and alumni association, a list of selected practitioners was developed, which contains 1000 senior managers, project managers, and project engineers.

From December 2015 to March 2016, a total of 1000 questionnaires were disseminated to the selected practitioners and 264 valid responses were received, representing a response rate of 26.4%. A valid response refers to the questionnaire that includes one political risk case, and all the questions were completed and appropriately filled out. As indicated in Table 2, 67.4% respondents were from the CCEs that were selected from the 2015 top 250 international contractors according to ENR's report, and 32.6% respondents were from other CCEs; 19.7% respondents were senior managers, and 80.3% respondents were project managers or project engineers. All the respondents had over 5 years of work experience, and 68 respondents had over 20 years of work experience. Among the 264 respondents, 113 were from Asia, 101 from Africa, and the other 40 from Oceania, Europe, and South America.

Apart from the data collected from the questionnaire, the matched data on the factors in groups A to H were collected from various secondary sources—the country report from the Chinese Ministry of Commerce (F2 and F3), the operational risk model from the Economist Intelligence Unit (EIU) (A2, B1–B5, C1–C5, D1–D4, and E1–E3), and the International Country Risk Guide (ICRG) from the PRS Group (A1, A3, and F1). All data with different dimensions were converted to the scale of 0 to 1.

3.2. Structural Equation Modeling (SEM). Structural equation modeling (SEM) is a multivariate statistical analysis method that has been widely used to analyze the structural relationship between measured variables and latent constructs [31, 32]. This method is the combination of confirmatory factor analysis (CFA), path analysis, partial least squares path modeling, and latent growth modeling [33].



(+) indicates the positive correlation between two groups

(−) indicates the negative correlation between two groups

Figure 1: Hypotheses of the political risk paths.

Table 2: Profile of the respondents.

Characteristics	Categorization	*N*	%
Enterprise scale	ENR top 250	178	67.4
	Others	86	32.6
Job title	Senior manager	52	19.7
	Project manager	164	62.1
	Project engineer	48	18.2
Work experience	5–10	89	33.7
	11–15	79	30.0
	16–20	68	25.8
	Over 20 years	28	10.6
Location	Asia	113	42.8
	Oceania	13	4.9
	Africa	101	38.3
	Europe	6	2.3
	North America	5	1.9
	South America	26	9.8

SEM consists of the measurement model and the structural model. The measurement model expresses the relationships between the latent variables and their measures (observed variables). The structural model examines the relationships among latent variables [34]. Compared with other multivariate analysis methods, SEM has the superiority of (1) estimating multiple and interrelated dependence relationships, (2) representing unobserved concepts in these relationships, (3) testing measurement errors in estimates, and (4) defining a model explaining an entire set of relationships [35, 36].

In view of the aforementioned advantages, the SEM technology was applied to test the hypotheses of this study. First, CFA was conducted with the measurement model to test whether the nine groups can be measured by the 29 political risk factors and 3 political risk consequences. In the measurement model, the 29 political risk factors and 3 political risk consequences were viewed as 32 observed variables and the nine groups were viewed as the nine latent variables. After the measurement model was reliable and valid with a good goodness of fit, the path analysis was conducted with the structural model to test the hypothesized relationships among the nine latent variables.

Generally, the reliability and validity of the measurement model were measured by the following methods: the factor loadings ≥0.500, the composite reliability (CR) value ≥0.70, the average variance extracted (AVE) value ≥0.500, and correlation between any two groups ≤ the square root of the AVEs of them [37–39]. In the structural model, the significance of the direct relationship between two latent variables is determined by the *t*-value for a two-tailed test (with ≥1.650 representing the significance at the $p = 0.10$ level, ≥1.960 representing the significance at the $p = 0.05$ level, and ≥2.580 representing the significance at the $p = 0.01$ level) [40, 41].

4. Results

4.1. Results of CFA. Before confirmatory factor analysis, the Cronbach alpha values of the nine groups were measured to test the data's reliability. All of them had the Cronbach alpha values greater than 0.700, indicating the received data are sufficiently reliable [38].

In the progress of model measurement and modification, "speediness of judicial process" (B5) and "kidnapping or extortion" (C5) were removed due to their low values of factor loading. As shown in Tables 3 and 4, the factor loading of remaining 30 factors ranges from 0.712 to 0.903 (≥0.500), the CR of the nine groups ranges from 0.829 to 0.914 (≥0.500), the AVE of the nine groups ranges from 0.548 to 0.726 (≥0.500), and no correlation between any two groups is higher than the square root of the AVEs of them, which provided the evidence of discriminant validity of the groups. Thus, the final measurement model was reliable and valid for the structural model.

4.2. Results of Path Analysis. The hypothesized causal relationships among the nine groups were tested by the structural model. As shown in Table 5, among the 18 hypothesized political risk paths, 14 political risk paths were supported and other four political risk paths were not supported. Clearly, "D → A," "D → B," "D → C," "A → B," "A → C," "B → I," and "C → I" were significant at the $p = 0.01$ level; "E → I,"

Table 3: Measurement model evaluation.

Factors	Factor loading	R^2	CR	AVE
A1	0.712	0.507		
A2	0.751	0.564		
A3	0.816	0.513		
			0.804	0.579
B1	0.827	0.684		
B2	0.752	0.566		
B3	0.870	0.757		
B4	0.781	0.610		
			0.883	0.654
C1	0.813	0.564		
C2	0.817	0.513		
C3	0.903	0.815		
C4	0.735	0.540		
			0.890	0.671
D1	0.756	0.572		
D2	0.846	0.716		
D3	0.912	0.832		
D4	0.887	0.787		
			0.914	0.726
E1	0.774	0.599		
E2	0.821	0.674		
E3	0.843	0.711		
			0.854	0.661
F1	0.825	0.681		
F2	0.777	0.604		
F3	0.756	0.572		
			0.829	0.619
G1	0.855	0.731		
G2	0.732	0.536		
G3	0.821	0.674		
			0.846	0.647
H1	0.811	0.658		
H2	0.792	0.627		
H3	0.866	0.750		
			0.863	0.678
I1	0.783	0.613		
I2	0.899	0.808		
I3	0.836	0.699		
			0.878	0.707

"G → I," and "H → I" were significant at the $p = 0.05$ level; "A → I," "F → C," "F → D," and "D → I" were significant at the $p = 0.10$ level; and "D → E," "F → A," "F → D," and "F → E" were not significant. Among the 8 factors, 7 (A, B, C, D, E, G, and H) had the directly negative effect on "risk consequences" (I), and 3 (A, D, and F) had the indirectly negative effect on "risk consequences," indicating that the poor performance of those factors was associated with increased political risk.

5. Discussion

5.1. Sociopolitical Stability. "Sociopolitical stability" (A) was reflected by three factors with significant loading: "government stability" (A1), "factional conflicts" (A2), and "religious and ethnic tensions" (A3). The results showed that "sociopolitical stability" (A) had a positive effect on "legal and regulatory" (B) and "public safety" (C) and a negative effect on "risk consequences" (I). The finding was in line with the study maintaining that the poor performance of sociopolitical stability has both the directly and indirectly negative influence on international construction projects [7]. On the one hand, government instability can result in repudiation or breach of a specified commitment by the host government to the guarantee holder; on the other hand, sociopolitical instability can cause an abrupt change of laws or regulations, poor enforceability of contracts, and deterioration of safety conditions [18, 42] and thereby influence the projects under consideration. The continuous conflicts between different political groups, religions, and nationalities might trigger chaos of economy, law, and order [18], which in turn detrimentally affect the business activities [19]. Moreover, the host government plays the dominant role in the social security governance; thus, an unstable government is utterly incompetent to create a secure environment for international investors [43]. Furthermore, the relationship between "sociopolitical stability" (A) and "international environment" (F) was not significant. The reason is that sociopolitical stability is mainly determined by the national conditions of host countries without the tremendous changes in the international political, economic, and social circumstance.

It is crucial for ICEs to evaluate the sociopolitical stability of the target market before they enter a country [44]. In countries with sociopolitical instability, ICEs should keep low involvement with the political and religious groups to avoid getting involved in the conflict. Choosing sole venture projects or joint venture projects with short durations can help ICEs reduce their exposure to environmental fluctuations [7, 45]. Besides, obtaining the corresponding guarantee, buying risk insurance, and constantly monitoring evolving conditions are useful to deal with negative political events [44, 46].

5.2. Legal and Regulatory. "Legal and regulatory" (B) was estimated by three factors with significant loading: "poor enforcement mechanisms" (B1), "policy uncertainty" (B2), "unfairness of judicial process" (B3), and "price controls" (B4). "Legal and regulatory" (B) had a significantly negative effect on "risk consequences" (I). ICEs operating in countries with the unsound legal and regulatory may suffer from the risks related to improper construction procedures, illegal bid activities, illegal interferences, breach of contracts, and frequent change of the law [4, 7]. Regarded as complicated trading and involving the benefits of multiparties, international construction business requires the criterion and guarantee of the legal and regulatory [20]. However, in some countries, the poor enforcement mechanisms and unfairness of judicial process make ICEs difficult to safeguard their legitimate rights and interests in resolving disputes. ICEs will be restless and adrift in the countries with unfair price controls and vague laws and regulations. When the law lost its function of guidance and evaluation, the demarcation of legal or illegal has become unclear, people cannot logically predict their own

Table 4: Discriminant validity of the nine groups.

Grouping	A	B	C	D	E	F	G	H	I
A	**0.761**	—	—	—	—	—	—	—	—
B	0.598	**0.809**	—	—	—	—	—	—	—
C	0.472	0.253	**0.819**	—	—	—	—	—	—
D	0.607	0.446	0.589	**0.852**	—	—	—	—	—
E	0.135	0.067	0.051	0.097	**0.813**	—	—	—	—
F	0.112	0.077	0.406	0.264	0.321	**0.787**	—	—	—
G	0.131	0.118	0.109	0.165	0.098	0.035	**0.804**	—	—
H	0.056	0.312	0.211	0.236	0.178	0.263	0.089	**0.823**	—
I	−0.178	−0.473	−0.289	−0.335	−0.097	−0.125	−0.238	−0.343	**0.841**

Note. Bolded numbers are the square root of the AVEs.

Table 5: Path coefficients and significance.

Path	Coefficient	t-value	Interpretation
F → A	0.097	1.116	Not supported
F → C	0.265*	1.894	Supported
F → D	0.278*	1.713	Supported
F → E	0.134	1.332	Not supported
D → A	0.484***	5.389	Supported
D → B	0.567***	6.258	Supported
D → C	0.632***	10.021	Supported
D → E	0.175	1.602	Not supported
D → I	−0.248*	1.753	Supported
A → B	0.611***	9.876	Supported
A → C	0.445***	6.214	Supported
A → E	0.123	0.935	Not supported
A → I	−0.235*	1.851	Supported
B → I	−0.373***	4.712	Supported
C → I	−0.328***	3.351	Supported
E → I	−0.246**	2.393	Supported
G → I	−0.289**	2.351	Supported
H → I	−0.257**	1.989	Supported

Note. *Path is significant at the $p = 0.10$ level. **Path is significant at the $p = 0.05$ level. ***Path is significant at the $p = 0.01$ level.

consequence of action according to law, and the market will be plunged into confusion [21, 22].

ICEs should act strictly according to the local law to avoid the unnecessary disputes caused by their own mistakes. Keeping good relationships with host governments and powerful groups are helpful for ICEs to obtain more support and benefits (e.g., convenient approval procedures, less government intervention, unblocked information and communication channels, and sufficient government guarantees) [3]. Furthermore, the skills and experience of local partners (e.g., lawyers, subcontractors, suppliers, and agencies) would be effective assistances for ICEs to safeguard their rights and interests under the unfamiliar legal conditions [47, 48].

5.3. Social Safety. Four factors had high loadings on “social safety” (C): “crime” (C1), “terrorism” (C2), “violent demonstrations” (C3), and “armed conflicts” (C4). The results showed that “social safety” (C) had a remarkable negative influence on “risk consequences” (I). Security is essential for international business activities. An unsafe environment will bring tremendous threats to the personnel and property safety of international contractors [4, 23]. Over past few decades, ICEs have been plagued with the political risks aroused from social safety around the world, such as the armed conflicts in Yemen, Honduras, Syria, Afghanistan, and Libya; the terrorist attacks in Mali, Iraq, and India; the kidnappings in southern Sudan, Pakistan, and Somalia. Thus, how to ensure security becomes a difficult issue which various ICEs need to solve.

Formulating emergency plan and providing staff for self-protection training are important for ICEs in an unsafe country [44, 49]. Closed management of construction sites with security systems (e.g., security guards, monitoring devices, and alarm mechanisms) might be helpful for ICEs to isolate crime, terrorist attacks, violent demonstrations, and armed conflicts [4]. Under the severe security situation, such as armed conflicts, wars, and terrorist attacks, ICEs should stop construction and evacuate from the danger area immediately.

5.4. Economy Performance. “Economy performance” (D) contained four factors with significant loading: “inflation” (D1), “unemployment” (D2), “exchange rate volatility” (D3), and “recession” (D4). “Economy performance” (D) was identified as a critical political risk factor that had a positive effect on “sociopolitical stability” (A), “legal and regulatory” (B), and “public safety” (C) and a negative effect on “risk consequences” (I). Poor economic performance can cause not only macroeconomic risk but also social and political unrest, which in turn detrimentally affect the international construction projects [29]. During the time of inflation, the purchasing power of currency will decline, imposing a cost on those ICEs who have used the fixed price contract. In general, ICEs are paid in local currency or hard currency and adverse volatility of exchange rate and interest rate would bring huge losses to ICEs [50]. In some countries, the high unemployment rate and inflation rate act as two important drivers for sociopolitical instability [24, 25]. In addition, most studies support the notion that social safety has a clear relationship with the economy performance. A long period of the depression can result in the disorder in both social value and the morality, and further intensify the society contradiction and the occurrence of crime [51].

Diversified investing in different countries can reduce firm risk [52]. In the countries with the high level of macroeconomic risk, ICEs should adopt appropriate contracts (e.g., escalation lump sum and cost-plus-fixed fee) to transfer the risks to owners [53]. When ICEs have some unavoidable risks, retaining the premium for those risks is an available strategy to reduce potential losses [54]. Furthermore, ICEs must constantly pay attention to the volatility of prices and hoard material in anticipation of inflation.

5.5. Attitude towards Foreigners. "Attitude towards foreigners" (E) was estimated by three factors with strong loading: "hostility to foreigners" (E1), "confiscation or expropriation" (E2), and "discrimination against foreign companies" (E3). It is identified that "attitude towards foreigners" (E) had a significantly negative effect on "risk consequences" (I). Meanwhile, the relationships between "attitude towards foreigners" (E) and "economy performance" (D), "international environment" (F) and "sociopolitical stability" (A) were not remarkable. The reason is that "attitude towards foreigners" (E) can be treated as an independent factor in these political risk cases, which has no regular pattern within different social cultural systems. There will be more obstacles and threats (e.g., public opposition, riots, political interference, and unjust treatment) for ICEs in those countries with racism and xenophobia. Furthermore, the attitude of the government to foreigners has a strong relationship with foreign policymaking [55]. The unfavorable foreign policy made by host governments can be regarded as a signal of various risks such as confiscation or expropriation, foreign investment restrictions, land ownership restrictions, unfair compensation, foreign exchange restrictions, and capital restrictions.

ICEs can preferentially access to the countries that have good relations with their home countries to seek more recognition and less opposition [4]. Localization strategies (e.g., tying-up with local businesses, forming a joint venture with local contractors, and employing the natives) would be helpful for ICEs to blur their image as foreigners, and thereby reduce their probability of being treated with discrimination and opposition [8, 44]. Moreover, participating in local public welfare activities, cultivating a good image via propaganda, beneficent to environment protection, and abiding by the local culture can help ICEs obtain social recognition, resources, opportunities, and support and further to achieve value creation in the host country.

5.6. International Environment. "International environment" (F) encompassed three factors with high loading: "external conflicts" (F1), "international economic crisis" (F2), and "external interferences" (F3). As shown in Figure 2, "international environment" (F) had a significant positive effect on "social safety" (C) and "economy performance" (D), but an insignificant effect on "sociopolitical stability" (A) and "attitude towards foreigners" (E). The results indicating that the unstable international environment has the capacity to affect the economy and safety of most countries. External conflicts (e.g., latent conflict, manifest conflict, crisis, severe crisis, and wars) can potentially destabilize the social safety of host countries [28]. International economic crisis and external interferences (e.g., foreign pressures, economic sanctions, embargoes, and international boycotts) would result in host countries' economy depression [6, 24, 30].

ICEs should always pay close attention to the changes in the international situation and adjust their operation strategies and project plans accordingly. Furthermore, establishing strong business councils and associations would be helpful to improve enterprises' existence ability.

5.7. Low Exposure. Three factors were strongly related to "low exposure" (G): "low attribute exposure" (G1), "low strategy exposure" (G2), and "low transaction-based exposure" (G3). "Low exposure" (G) was confirmed having a significantly negative effect on "risk consequences" (I). Attribute-based exposure would be related to the characteristics of projects and ICEs, such as longer duration, lower technical complexity and managerial complexity of projects, and misconduct of enterprises [50]. Strategy-based exposure may be related to the smaller size of subsidiary or enterprise, and unreasonable arrangements of leverage choice and ownership. Transaction-based exposure would be related to lower project desirability to the host country, insufficient external funding of the project, and disadvantageous conditions of the contract. The ICEs with lower risk exposure would have a higher capability to mitigate uncertainties [17, 56].

It is necessary for ICEs to reduce their risk exposure in high risk areas. The available strategies that help ICEs reduce risk exposure include: avoiding misconduct, choosing suitable entry mode and projects, allocating extra funds, and obtaining the corresponding guarantee.

5.8. Capability of Enterprises. Three factors were involved in "capability of enterprise" (H) with strong loadings: "core competitive capacity" (H1), "relative bargain capacity" (H2), and "integrate adaptive capacity" (H3). "Capability of enterprises" (H) had a significantly negative effect on "risk consequences" (I). A higher risk response capability of an ICE indicates that it has higher viability in an uncertain environment and is less likely to suffer damage arising from political risk [17]. Core competitive capacities include rich experience, high localization, and stable relationships with host governments and power groups. The ICEs with superior core competitive capacities are regarded to have excellent viability and superior profitability [57]. Relative bargain capacity is related to the technology or resources that are needed by the host governments. The ICEs with the higher bargain capacity are expected to get advantageous terms of the contract [58]. Integrate adaptive capacities include high involvement of local business interests, adaptive organizational culture, and significant economic contribution to the local economy. The ICEs with greater integrate adaptive capacities would be more acceptable for the host governments and the society [29, 59].

The cultivation of capability is a long-term process for ICEs. Fortunately, ICEs can make up their own weakness and thereby improve their corresponding capabilities by choosing the right partners.

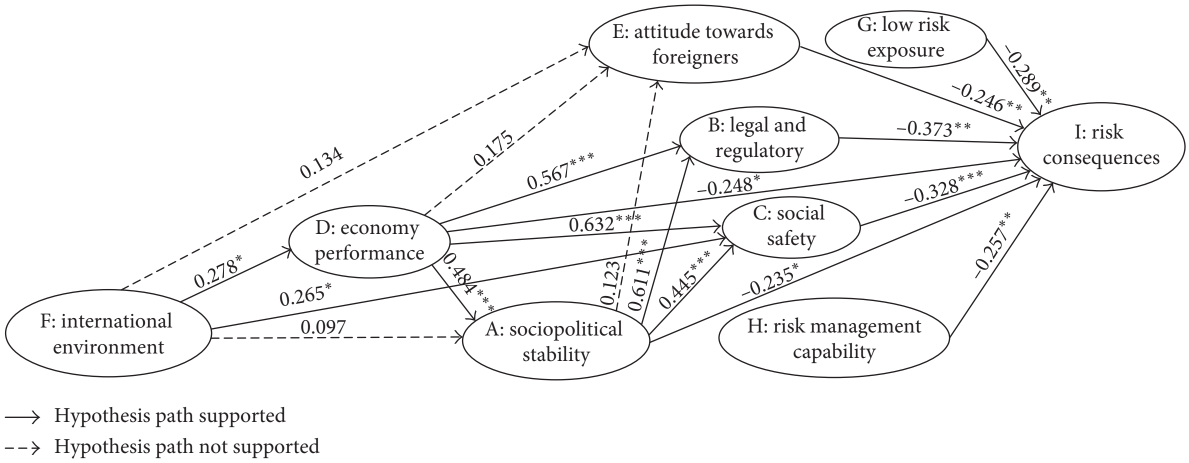


Figure 2: Networking of political risk paths. *Significance at the $p = 0.10$ level, **significance at the $p = 0.10$ level, and ***significance at the $p = 0.10$ level.

5.9. Risk Consequences. "Risk consequences" (I) was measured by three factors with high loading: "profits" (I1), "stability and sustainability" (I2), and "safety" (I3). As illustrated in Figure 2, "risk consequences" (I) was significantly influenced by "sociopolitical stability" (A), "legal and regulatory" (B), "social safety" (C), "economy performance" (D), "attitude towards foreigners" (E), "low exposure" (G3), and "capability of enterprises" (H) and indirectly influenced by "international environment" (F). These findings support the standpoint that the political risk level of international construction projects are not only influenced by the fluctuations in the external environment, but also affected by the characteristics of projects and firms [17].

While political risk is difficult to forecast and eliminate, it can be moderately addressed by reducing the risk exposure of the project system and improving the capability of enterprises. Successful political risk management is dependent on sufficient resources and information [60]. Political risk not only affects the performance of international construction projects, but also affects the objectives of ICEs (e.g., financial, reputation, stability, survival, development, and strategic decision) [3, 9, 61]. Thus, ICEs should treat political risk as part of the entire risk portfolio and address it across multiple business areas. Generally, political risk management in international constriction projects should (1) be based on a comprehensive understanding of political risks; (2) be treated as an important component of the decision-making process; (3) emphasize both the projects' short-term and enterprises' long-term goals; and (4) be continually enhanced with the accumulation and sharing of risk management experience.

6. Conclusions

This study attempted to explore the political risk paths in international construction projects. Based on the 264 political risk cases collected from 30 CCEs performing international construction projects, a total of 8 political risk factors and 14 significant political risk paths were identified. Consistent with previous studies, the macrofactors ("sociopolitical stability" (A), "legal and regulatory" (B), "social safety" (C), "economy performance" (D), "attitude towards foreigners" (E), and "international environment" (F)) were associated with the external threats in the overseas construction market. The microfactors ("low exposure" (G) and "capability of enterprises" (H)) were related to the internal vulnerability project systems. Among the 8 factors, 7 (A, B, C, D, E, G, and H) had the directly negative effect on "risk consequences" (I) and 3 (A, D, and F) had the indirectly negative effect on "risk consequences." Based on the understanding of the effects of these political risk factors, the coping strategies, for example, choosing a suitable entry mode, choosing suitable projects, maintaining good relations with powerful groups and host governments, diversification investing in different countries, obtaining the corresponding guarantee, buying risk insurance, adopting perfect contract, employing capable local partners, implementing a localization strategy, making contingency plans, sending staff to training programs, and allocating extra funds, were developed for ICEs to address the political risk in the global market.

The practical implications that can be drawn from this study are as follows:

(1) ICEs should be sensitive to those political risk factors and take them as the indicators for political risk assessment.

(2) Since political risk in international construction projects is not only influenced by the external threats, but also affected by the internal vulnerabilities, ICEs can moderately address political risk by reducing risk exposure of the project system and improving their capability.

(3) ICEs should realize that political risk at the project level can also affect enterprise's objectives (e.g., financial, reputation, stability, survival, and development) and conduct political risk management practices at both the project and firm level and link risk management strategies to the enterprise's objectives.

(4) ICEs should suit their political risk management strategies to different conditions in terms of locality, time, issue, and people involved.

The primary limitation of this study is that most of the political risk cases (in total 81.1%) were collected from the projects located in Africa and Asia, but relatively few were collected from other overseas markets. According to the ENR's report, Africa and Asia have been the two largest overseas markets of CCEs in recent years. Therefore, the region distribution of the samples is consistent with the distribution of the projects performed by CCEs. Due to the inability to predict before the survey whether the practitioners would be willing to participate in the survey, the received political risk cases can be regarded as a non-probabilistic sample, which has been recognized as the representative sample [62]. Despite the limitation, the practical implications of this study are not limited in CCEs because the situations in the global market are generally the same for all ICEs. Therefore, it is believed that this study makes a significant contribution to the knowledge of political risk management in the international construction business.

Further research would be conducted to examine the political risk management strategies in different enterprises and different countries to increase the practical validity.

Data Availability

The data of the 264 political risk cases used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Key Success Indicators for PPP Projects: Evidence from Hong Kong

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Because a consensus has yet to be reached on how to assess the success of a Public-Private Partnership (PPP) project, it is meaningful to study the multidimensional indicators to assess PPP project success. It merits attention that PPP project success indicators are totally different from PPP critical success factors (CSFs), which have attracted a lot of attention from scholars. This study conducts a questionnaire survey to identify the crucial considerations of project success from the perspectives of different PPP stakeholders. In line with previous studies, five dimensions of PPP project success that were developed from different stakeholder viewpoints and time frameworks were tested based on the empirical data. The dimensions mapped in the study not only provide a benchmark for practitioners to diagnose the extent of PPP project success but also provide a solid foundation for scholars to conduct further studies regarding PPP project success.

1. Introduction

As a new approach to gathering the skills, technologies, and resources of different stakeholders, a large-scale project procured in Public-Private Partnership (PPP) could be issued and managed as a whole rather than as small pieces that are conducted in a consecutive manner to meet the requirements of time and cost in the traditional procurement method. Therefore, PPP bridges the gap between design, construction, and facility management roles and provides better services with lower life-cycle cost. Although the project outcomes would benefit from the continuity and cooperation relationship of a PPP approach, more risks are triggered by the complexity, long-term nature, and varied stakeholders of PPP projects. Even though the PPP approach has been widely adopted in a large number of projects, promoting the application of PPP is still debatable in both the industry and academia. The source of the debate lies in the lack of a comprehensive evaluation system to assess the performance of PPP projects.

Actually, the effectiveness of the "iron triangle" criteria, which are widely adopted to measure traditional construction projects, has been widely applied to evaluate the success of PPP projects. However, the "iron triangle" criteria are too simple to reflect the expected outcomes of stakeholders for the performance of PPP projects. This is because the goal of the radical PPP approach is to procure services and/or facilities rather than assets. The goal is significantly different from that of the traditional procurement approach. A successful PPP project should also meet the objectives and anticipation of most stakeholders, including the end users. Additionally, different stakeholders would recognize project success from different viewpoints in line with their benefits. Therefore, the research question is whether it is possible to build comprehensive indicators to evaluate PPP project performance that can reflect most stakeholders' opinions and what types of projects can be regarded as successful.

The objective of this study is to identify the key success indicators of PPP projects. To achieve this objective, a questionnaire survey was conducted to collect the empirical data from Hong Kong and investigate the crucial considerations of different PPP stakeholders into the PPP project success. The study intends to contribute to the existing literature on the key success indicators for measuring PPP and, specifically, to deliver meaningful implications for evaluating PPP project success.

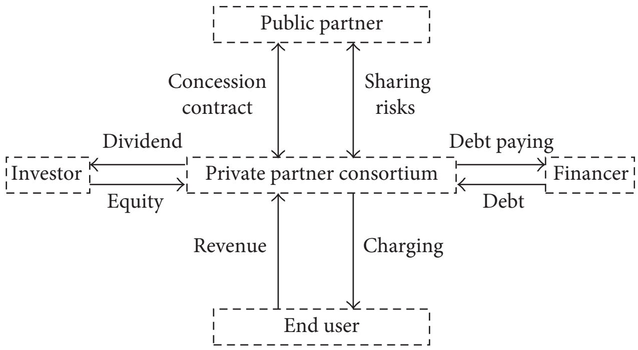

Figure 1: Schematic correlation of a Public-Private Partnership project.

2. Background

Project success indicators should be distinguished from project management success and project success factors. The main theme of project management success is assessing the potency of project management processes, while the substance of project success is investigating the extent of fulfilment of the established goals [1–3]. Project success can be achieved only if the project management process follows the correct direction. Although there are connections between project success indicators and project success factors, success indicators refer to standards that measure success, whereas success factors represent the events contributing to success [4, 5]. It is well known that the acknowledged early project success indicators, often referred to as the "iron triangle," are closely associated with "hard" project objective measures, including schedule, cost, and quality standards. The "soft" subjective measures, especially the satisfaction of stakeholders, are ignored in the "iron triangle" criteria [6]. Through a combination of hard and soft measures, one common accepted criterion for evaluating project success is whether a project meets the requirements of time, cost, technical specification, and client satisfaction [7, 8]. In fact, the client is among the multiple stakeholders. It should be noted that stakeholders refer to not only the parties within the project but also the parties that could affect or be affected by project implementation [9, 10]. In other words, a project could be recognized as a successful one only if the individual or mutual expectations of the stakeholders are met [1].

As a specific construction procurement approach, PPP is usually applied in infrastructure construction projects that have significant effects on social or economic development and are closely associated with different stakeholders' interests [11, 12]. Nisar [13] highlights the intrinsic features of the PPP approach: the private sector is responsible for financing, managing assets, and charging in accordance with the performance of assets or the extent of asset usage by either the clients or end users. Therefore, the primary correlations in PPP are shown in Figure 1.

It is clear that a PPP project is initiated and granted by a public partner resort to a concession contract, while the private partner finances, designs, builds, operates, and maintains the project strictly abiding by the concession contract. The ultimate outcomes of the project are used by the end users [14, 15]. Accordingly, the key stakeholders in this study are composed of three components, namely, a public partner, a private partner, and end users. Given the special arrangement of a PPP project, it is important to emphasize the end user as a main stakeholder as the responsibility for providing services is transferred from the public partner to the private partner. Therefore, the end users' interests are inevitably affected. In fact, taking stakeholders' benefits into consideration is consistent with the intrinsic essence of shareholder value (SV) management. SV management and balanced scorecard (BSC) are the two measurement systems that can be used to improve organizational performance. SV management is useful for overcoming the overinvestment problem and underinvestment problem in traditional financial performance measurement. The BSC approach is a strategic planning and management system that aligns business activities with the vision and strategy of the organization, improves internal and external communications, and monitors organization performance against strategic goals. The BSC approach has been widely adopted to evaluate the overall performance of construction firms and projects. It is notable that the essence of the PPP procurement approach is in accordance with the core contents of SV management and the BSC approach. Consequently, both financial and nonfinancial measures should be taken into account when exploring the success indicators of a PPP project.

In addition to diversified participants, the life cycle of a PPP project is much longer than that of a general construction project. In general, the concession period of a PPP project is longer than 20 years, in which the design and construction stages are relatively shorter than the operation stage. Therefore, for judging PPP project success, long-term characteristics have to be considered in the PPP project success indicators. The success indicators of PPP projects are listed in Table 1.

Shenhar et al. [16] used 13 project success measures extracted from previous studies and indicated that these measures could be categorized into four dimensions of project success in terms of time framework. The first dimension relates to the short-term objective of project efficiency. This dimension of project success could be evaluated after the design and construction of the project are completed. The second dimension of project success is associated with the medium-term objective of the effect on the stakeholders or customers. The third dimension of project success addresses the long-term objective of business success, while the fourth dimension of project success focuses on the long-term objective of preparing for the future. Dvir et al. [17] measured defence project success based on the three criteria, including the five measures related to the criterion of "meeting planning goals," seven measures focused on the criterion of "end-user benefits," and nine measures connected to the criterion of "contractor benefits." In addition, Sadeh et al. [18] developed and classified project success into 4 dimensions based on time-dependent criteria and stakeholders' viewpoints. Dimension 1 is entitled "meeting design goals," which is similar to the classification of Shenhar et al. [16]. Dimension 2 focuses on the benefits to

Table 1: Success indicators of PPP projects.

Number	Dimensions/measures of success indicators	References
1	Dimension 1: project efficiency Dimension 2: impact on the customer Dimension 3: direct business and organizational success Dimension 4: preparing for the future	Shenhar et al. [16]
2	Dimension 1: meeting planning goals Dimension 2: end-user benefits Dimension 3: contractor benefits	Dvir et al. [17]
3	Dimension 1: meeting design goals Dimension 2: benefits to the end user Dimension 3: benefits to the development organization Dimension 4: benefit to the defence and national infrastructure	Sadeh et al. [18]
4	Measure 1: acceptable quality of project Measure 2: quality public service Measure 3: within budget or saving money in construction and operation Measure 4: on-time or earlier project completion Measure 5: satisfying the need for public facilities Measure 6: provide timelier and more convenient service for society Measure 7: solving the problem of public sector budget restraint Measure 8: life-cycle cost reduction Measure 9: introducing business and profit-generating skills to the public sector Measure 10: transferring risk to private sector Measure 11: making profit from public service Measure 12: promoting local economic development Measure 13: improving technology level or gaining technology transfer Measure 14: public sector can acquire additional facilities/services beyond requirement from private sector Measure 15: private sector can earn government sponsorship, guarantees, and tax reductions	Yuan et al. [19]

the end users. Dimension 3 emphasizes the benefits to the developing organization, which not only investigates the tangible profits but also explores the intangible benefits to the organization such as reputation. Dimension 4 is "benefit to the defence and national infrastructure." Yuan et al. [19] established a conceptual KPIs framework in line with 15 performance objectives selected. The KPIs are useful to assess performance of PPP projects. Given the long-term traits and complex stakeholder relationships in a PPP project, we will explore the key success indicators of PPP projects from the perspectives of the main stakeholders using a time-dependent framework.

3. Methodology

3.1. Selection of Measures and Items. Based on a literature review of project success indicators and the specific characteristics of PPP projects, PPP project success was developed and measured in line with the five dimensions. Dimension 1 is "meeting design goals," which refers to the short-term effects of the project and can be judged after the project design and construction are complete. Dimensions 2 through 4 (i.e., "benefits to end user," "benefits to private partner," and "benefits to public partner") investigate the medium-term influences of the project because the impacts of the project on these stakeholders can be assessed only if the concession contract ends. The last dimension is "preparing for the future," which is introduced to capture the long-term impact of the project on the entire industry and social development. The item scales used to measure "meeting design goals" are organized based on the viewpoints of Shenhar et al. [16]. The items used to measure the "benefits to end user" are developed based on the findings of Dvir et al. [17], Shenhar et al. [20], and Zhang [21]. The questionnaire items used to study on the "benefits to private partner" consist of two parts. Most items are extracted and refined in accordance with the validated item scale used in Dvir et al. [17]. Meanwhile, one item is developed in line with the findings of Zhang [21] and Li et al. [22]. The new item is highly related to PPP benefits. The items adopted to measure the "benefits to public partner" are extracted and developed based on the findings of Akintoye et al. [23] and

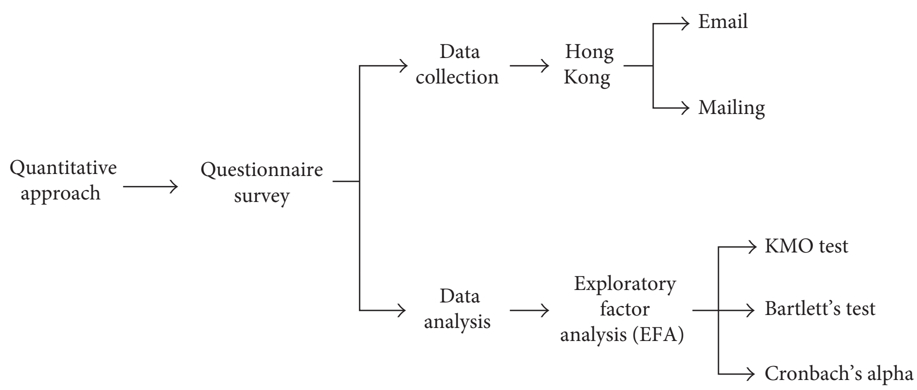

Figure 2: Research design.

Zhang [21]. These items are closely related to PPP superiority. To measure "preparing for the future," items are developed based on the items used by Walker and Rowlinson [24] and modified to PPP projects according to the findings of Li et al. [22].

3.2. Methodology of Data Collection and Analysis. In this study, the quantitative approach was adopted and is briefly illustrated in Figure 2.

3.2.1. Data Collection. Because the questionnaire survey technique has been widely used to collect professional views in construction management research [25–29], this study collected the data of critical success indicators of PPP projects via an empirical questionnaire survey. The questionnaire was prepared and fine-tuned through pilot study and discussions with various stakeholders in PPP projects, including government authorities, construction managers, architects, and engineers. To improve the response rate, a cover letter was attached to encourage unqualified respondents to forward the questionnaire to people who were willing and eligible to participate in the survey. The respondents were requested to rate their degree of agreement against the success indicators according to the five-point Likert scale. Specifically, values 1 through 5 were assigned from greatest disagreement to greatest agreement, respectively.

To verify the questions and gauge the likely feedback solicited from respondents, a pilot study was conducted with experienced practitioners in the industry. To carry out a full-scale survey, experienced practitioners from the public, private, and other sectors were selected as potential respondents. Because there was no publicly available database of PPP participants, the potential respondents were selected from the following sources: architectural consultants listed by the Association of Architectural Practices, members of the Hong Kong Institute of Construction Managers, building contractors recognized by the Hong Kong Housing Authority, and the listed participants of several construction conferences. To eliminate the influence of ineligible sample to the overall sample, the mails returned due to incorrect or incomplete addresses, the respondents who no longer had the recorded job, the respondents who were out of the office, and the respondents who had little PPP experience were considered as the ineligible sample and excluded from the final analysis.

3.2.2. Data Analysis. The data collected from the survey were analysed using SPSS 19.0. Missing data are analysed using SPSS 19.0 with Little's MCAR test. The exploratory factor analysis (EFA) approach, which is widely used to handle large-scale question items and obtain useful information regarding critical factors based on the scores given by respondents [30–32], was employed in this study. As the most commonly used method to extract factors, principal components analysis (PCA) was employed along with the varimax rotation method in EFA to maximize the variance of the factor loadings [33]. It should be noted that two premises have to be satisfied before using EFA. The first one is to meet the requirement of the Kaiser–Meyer–Olkin (KMO) test of sampling adequacy. The principle of the KMO measure is to compare the magnitudes of observed correlation coefficients with the magnitudes of partial correlation coefficients [34]. To pass the KMO test, the value must be higher than 0.50. If the value is above 0.70, the sample is good enough for factor analysis [35]. In addition, the appropriateness of the sample should be verified through Bartlett's test of sphericity. The sample is appropriate for EFA only if the null hypothesis is rejected.

Using EFA, a large number of variables can be compressed into fewer factors with commonalities. Comrey and Lee [36] note that communality reflects the sum of squares of factor loadings over all of the factors. In social science research, the communality of items should be higher than 0.40 [37]. In addition to the communality check, the factor loading check is also crucial for factor extraction. In general, ±0.45 is recognized as the cut off value for factor loading [38]. In fact, even if the communality and the factor loading satisfy the requirements to extract factors, the number of principle components retained should be determined in line with the following principles: the first one is to retain the components with eigenvalues greater than 1.00. However, the number of components might be underestimated or overestimated occasionally if complying with only the first principle. To address this problem, a scree plot can be adopted as a complementary principle. The last step of factor extraction is to calculate the value of Cronbach's alpha, which is

Table 2: Demographic information of the respondents.

Variable	N	P
Role undertaken in a Public-Private Partnership project		
Public partner	14	18.18
Private partner	51	66.23
Others	8	10.39
Unknown	4	5.20
Public-Private Partnership project type		
Hospital	12	15.58
Transportation	27	35.06
Water and sanitary	2	2.60
Power and energy	4	5.20
Housing	17	22.08
Education	4	5.20
Defence and military	2	2.60
Others	9	11.68
Public-Private Partnership procurement approach adopted		
Build-own-operate-transfer (BOOT)	1	1.30
Design-build-finance-operate (DBFO)	30	38.96
Build-transfer-operate (BTO)	7	9.09
Build-operate-transfer (BOT)	13	16.88
Build-own-operate (BOO)	4	5.20
Build-lease-transfer (BLT)	3	3.90
Others	12	15.58
Unknown	7	9.09

Note. N is the number of effective replied questionnaires; P is the percentage of effective replied questionnaires.

utilized as a useful tool to test the internal consistency (or reliability) of extracted factors. Normally, if the value of Cronbach's alpha is equal to or greater than 0.70, the internal consistency of the extracted factors is acceptable [39]. Through a strong design of research structure and an exhaustive quantitative data analysis, realistic findings can be obtained from the research.

4. Results

4.1. Results of Data Collection. The response rate by post was 7.8%, while the response rate by email was 1.32%. After deleting those questionnaires with missing data, there were 77 valid records (73 records returned by post and 4 records gathered by email).

The response rate was relatively low compared with the 20%–30% norm of most construction surveys [40]. It is not surprising that the overall response rate was low within the construction industry. Because the potential survey respondents were practitioners in the overall construction industry rather than practitioners in the PPP field, the effective response rate seems not high enough. However, all the respondents were experienced PPP practitioners, and thus the collected data can reflect the reality of PPP practice in Hong Kong. For example, 64% of the respondents are the practitioners in PPP fields with more than 15 years of working experience and can provide valuable information for references. Moreover, the sample size met the basic requirement of empirical analysis [41]. Nevertheless, the results could be more robust with a larger sample size.

Accompanied by the questions related to project success, the respondents were requested to provide a variety of background information, including role undertaken in a PPP project and the project type and PPP procurement approach adopted in the project. Table 2 presents the demographic information of the respondents.

Compared with the private partners, it was difficult for public partners to participate in this study due to the difficulty in obtaining their contact information. The public partners involved in the study were from government departments and agencies. As for the private partner, the specific roles of respondents in projects are shown in Figure 3. Transportation projects represented the highest proportion. In addition to transportation projects, PPP approaches were also used in public housing and hospital projects. Among a large number of subsets of PPP approaches, Design-Build-Finance-Operate (DBFO) and Build-Operate-Transfer (BOT) were two of the most prevalent procurement approaches.

4.2. Results of Data Analysis. The descriptive data of the replied item scales belonging to each dimension of PPP project success of this study are shown separately in Tables 3–7.

The results of Little's MCAR test is $\chi^2 = 119.643$, $df = 114$, and $p = 0.340$. It is assumed that data are missing completely at random (MCAR) because no significant results were indicated by the missing data analysis. The result of MCAR suggests that variables of the missing data were not affected by any other variables or missing values themselves [42]. Accordingly, the missing data are imputed with the expectation maximization method.

As reported in Table 8, five factors are extracted based on the 25 question items. The value of the KMO test was 0.78, greater than 0.70, implying that the correlation matrix of the sample was good enough for EFA. In addition, the value of Bartlett's test of sphericity was 1419.12 ($p < 0.001$), which suggested that the sample was appropriate for EFA. According to the results of EFA, five factors, rather than six factors, were extracted. Although it is suggested to extract principle components in line with the correlation matrix's eigenvalue, a scree plot is taken into consideration with the eigenvalue [43]. According to Stern [33], only the factors with eigenvalues above the straight line should be kept if a line is drawn through the smallest eigenvalues on the scree plot.

Therefore, it is verified that 5 factors should be extracted in this study. Meanwhile, as indicated in the research Methodology section, after the sampling adequacy testing is finished and the preliminary factors are extracted, communalities should also be examined. In this study, the communalities of all the factors were higher than 0.40. Moreover, all the items had a factor loading greater than 0.50 on only one factor. Meanwhile, Cronbach's alpha of each factor was greater than 0.70, which suggested that the extracted factors were appropriate in terms of good internal

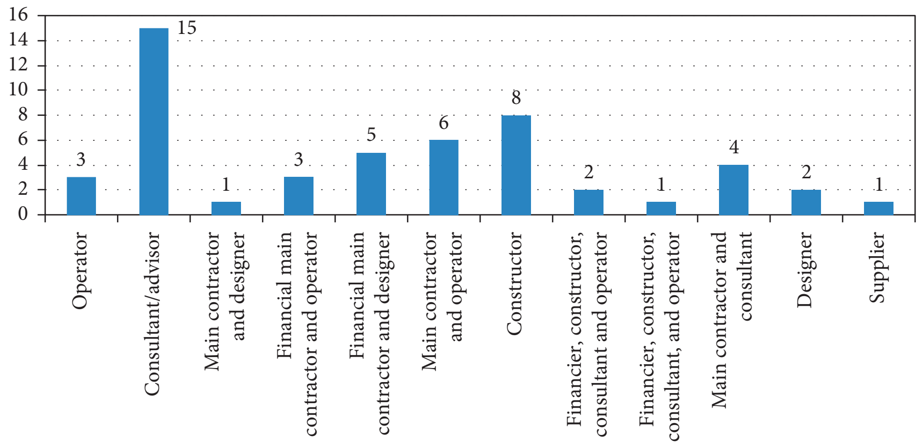

Figure 3: Descriptive data of 12 types of private partner respondents.

Table 3: Descriptive data of the project success dimension "meeting design goals."

Questions	*N*	Minimum	Maximum	Mean	Median	SD
Did the project outcome meet the schedule goal?	77	2	5	3.77	4.00	0.742
Did the project outcome meet the cost goal?	77	2	5	3.66	4.00	0.868
Did the project outcome meet the technical specifications?	77	2	5	3.81	4.00	0.762
Did the project outcome meet the functional requirements?	77	2	5	3.70	4.00	0.844

Table 4: Descriptive data of the project success dimension "benefits to end user."

Questions	*N*	Minimum	Maximum	Mean	Median	SD
Did the project outcome meet the end user's requirements of user charge?	77	2	5	3.70	4.00	0.796
Was the project outcome delivered to the end user on time?	77	1	5	3.73	4.00	0.968
Was the project outcome utilized for a long lifespan?	77	2	5	3.64	4.00	0.759
Has the project outcome substantially improved the end user's quality of life?	75	1	5	3.49	4.00	1.005
Is the end user satisfied with the project outcome?	77	2	5	3.61	4.00	0.905

Table 5: Descriptive data of the project success dimension "benefits to private partner."

Questions	*N*	Minimum	Maximum	Mean	Median	SD
Did the profits gained exceed the plans?	77	1	5	3.43	4.00	0.880
Did the profits gained exceed similar projects?	77	2	5	3.65	4.00	0.602
Has a new market been explored by the private partner?	76	2	5	3.75	4.00	0.733
Has a new technology been developed by the private partner?	77	2	5	3.57	4.00	0.818
Have new knowledge and expertise been developed by the private partner?	77	2	5	3.60	4.00	0.674
Has the private partner generated a positive reputation?	77	1	5	3.70	4.00	0.933
Could the private partner respond to a competitive threat through project implementation?	77	1	5	3.68	4.00	0.802
Was the project life-cycle cost controlled as expected?	77	1	5	3.73	4.00	0.772

consistency. After conducting the EFA, 25 items were reduced to five principle components. Taken together, the 59.77% variance of project success could be explained by the five extracted factors, in which the underlying grouped factors account for 11.37%, 5.43%, 25.99%, 7.90%, and 9.09% of the total variances, respectively.

Table 6: Descriptive data of the project success dimension "benefits to public partner."

Questions	N	Minimum	Maximum	Mean	Median	SD
Did the financial input of the government decrease as expected?	77	2	5	3.69	4.00	0.862
Was the government reputation improved through project implementation?	77	2	5	3.52	4.00	0.718
Was the service provided better than that of a traditional project?	77	2	5	3.75	4.00	0.797
Was the process to provide service shortened?	76	1	5	3.49	4.00	1.160

Table 7: Descriptive data of the project success dimension "preparing for the future."

Questions	N	Minimum	Maximum	Mean	Median	SD
Was the local economic development benefited by the project implementation?	76	2	5	3.63	4.00	0.846
Were innovative approaches developed in the project implementation?	75	2	5	3.79	4.00	0.890
Was a new outcome created by the project implementation?	75	2	5	3.84	4.00	0.772
Was the industry prepared to make changes for future challenges based on the project implementation?	74	1	5	3.74	4.00	0.861

5. Discussions

Although the factors extracted satisfied the requirements of the KMO test, Bartlett's test of sphericity and Cronbach's alpha, the results of EFA were slightly different from what we expected to explore in terms of the measures of PPP project success. The two items explored to test "benefits to end user" were regrouped into the dimension of "meeting design goals." After reviewing the meanings of items under the dimension of "meeting design goals," this factor is interpreted as "meeting planning goals."

The empirical findings revealed that PPP project success indicators were relatively complicated compared with the success measures of other projects. The conventional "iron triangle" measures reflect only one dimension of PPP project success. Although "the delivery time to end user" and "the charge fees for end user" are highly interrelated to the end-users' benefits, these two issues closely associated with the "iron triangle" are not taken into consideration when the end users judge PPP project success. Obviously, if the project outcomes reach the end user on time, the designed schedule goal is certainly met. Moreover, the market-oriented economy in Hong Kong leads to the reality that the user charge is directly at the mercy of the private partner's economic objective because cost and profit are the two components of the private partner's economic objectives. In addition, the user charge is closely related to one aspect of the "iron triangle": cost. As people live in a market-oriented economic system, the end users generally agree that good service deserves a higher charge. Consequently, charge fees and delivery time are not the prioritized considerations of the end users.

The dimensions explored and verified in this study were not only beneficial to overcoming the drawbacks of the "iron triangle" measures but also in line with the suggestions given by other researchers. For example, the short-term objective, the medium-term objective, and the long-term objective of implementing PPP projects should be considered when assessing the outcomes of a PPP project. Meanwhile, stakeholder satisfaction is also crucial for judging PPP project success. Among the dimensions tested in the paper, "meeting planning goals" is closely associated with the short-term objective of a PPP project. The three dimensions of "benefits to end user," "benefits to private partner," and "benefits to public partner" are closely related to the medium-term objective of PPP project and stakeholder satisfaction. The dimension of "preparing for the future" evaluates the long-term objective of the PPP procurement approach. In summary, the dimensions explored and divided based on the long-term and diversified participant characteristics of PPP projects are suitable for testing PPP project success.

On the contrary, significant correlations between the dimensions of project success indicators show that a successful PPP project has to meet the three objectives: the first objective is about the short-term goals of PPP project implementation, which are closely associated with the design and construction stages of a PPP project; the second objective is to satisfy the stakeholders' objectives that can be assessed only at the end of the concession contract; and the third one is to provide benefits for the entire industry and social development.

Dvir et al. [17] noted that the end users should join a PPP project at the beginning of the project and stay through the end of the project, implying a significant relationship between "benefits to private partner" and "benefits to public partner." However, the findings of our study revealed that neither the private partner nor the public partner benefits were significantly associated with "benefits to end user." This implied that the end-user benefits are not the major concern throughout the implementation of a PPP project and that the end user should be involved in PPP projects during the

Table 8: Exploratory factor analysis of Public-Private Partnership project success measures.

Question items	Com.	FAC 1	FAC 2	FAC 3	FAC 4	FAC 5
Did the project outcome meet the schedule goal?	0.619	0.744				
Did the project outcome meet the cost goal?	0.755	0.850				
Did the project outcome meet the technical specifications?	0.717	0.783				
Did the project outcome meet the functional requirements?	0.681	0.722				
Did the project outcome meet the end user's requirements of user charge?	0.598	0.601				
Was the project outcome delivered to the end user on time?	0.614	0.725				
Was the project outcome utilized for a long lifespan?	0.675		0.802			
Has the project outcome substantially improved the end user's quality of life?	0.640		0.611			
Is the end user satisfied with the project outcome?	0.633		0.739			
Did the profits gained exceed the plans?	0.622			0.755		
Did the profits gained exceed similar projects?	0.490			0.695		
Has a new market been explored by the private partner?	0.551			0.699		
Has a new technology been developed by the private partner?	0.578			0.551		
Have new knowledge and expertise been developed by the private partner?	0.426			0.622		
Has the private partner generated a positive reputation?	0.452			0.652		
Could the private partner respond to a competitive threat through project implementation?	0.503			0.691		
Was the project life-cycle cost controlled as expected?	0.503			0.645		
Did the financial input of the government decrease as expected?	0.540				0.732	
Was the government reputation improved through project implementation?	0.567				0.720	
Was the service provided better than that of a traditional project?	0.667				0.774	
Was the process to provide service shortened?	0.418				0.614	
Was the local economic development benefited by the project implementation?	0.649					0.763
Were innovative approaches developed in the project implementation?	0.753					0.821
Was a new outcome created by the project implementation?	0.656					0.751
Was the industry prepared to make changes for future challenges based on the project implementation?	0.634					0.750
Eigenvalue		2.842	1.357	6.496	1.976	2.271
Variance explained		11.369	5.426	25.985	7.904	9.086
Cumulative variance explained		11.369	16.795	42.78	50.684	59.771
Scale's Cronbach's alpha		0.875	0.725	0.839	0.701	0.812

Note. Com.: communalities; FAC 1: meeting planning goals; FAC 2: benefits to end user; FAC 3: benefits to private partner; FAC 4: benefits to public partner; FAC 5: preparing for the future.

initial period, which is crucial for improving the service provided by the private partner and achieving overall project success.

The results reflected the management reality. As the objective of a PPP project is to procure a better service, the primary issue for practitioners is "what is a better service." For the public sector and the end users, the better service not only means that a project with higher quality and lower cost should satisfy technical and functional requirements, but also that the project should be delivered to the end users as soon as possible with lower payment. Since the criterion of a better service is known, the next thing for practitioners is how to achieve it and make a project success. As the achievement of the objectives relies on outstanding technique and management skills of the private partner, the foremost step to secure the success of a PPP project is to select a qualified private partner. Meanwhile, because the implementation of a PPP project is to provide better services for the end users rather than mitigate the financial risk of the public partner, the end user's satisfactions are very important to appraise PPP project success. Therefore, to achieve the success of a PPP project, it merits attention that the benefits of the end users should be assigned with a priority over the interests of the private and public partners. If possible, the end users' opinions on a PPP project should be polled before the implementation. In addition, as the benefits of the private and public partners are closely interrelated, to achieve the success of a PPP project, both parties should consider the problems that would be encountered in the project from the perspective of their counterparts. Mutual understanding is considered as the basis of contracting. Of course, renegotiation could be considered as a useful approach to maximizing the interests of both parties if the contract is not perfect [44].

6. Conclusions, Limitations, and Future Work

To ensure the economic, environmental, and social development, the demand for effective success measures has been driven in these days. This study attempts to identify and develop success measures for PPP projects based on a questionnaire survey. The questionnaire survey is carried out to solicit professional opinions about the five-dimensional success indicators which are proposed according to the literature review and pilot interviews. These results showed that the five dimensions were really covered in practice despite differences in their relative importance. Compared with the basic demand for short-term goals to maximize the benefits of the private partner, medium-term and long-term measures related to economic and social benefits were much more important.

Although the findings have realistic and profound significances in theoretical and practical aspects, some limitations still exist. Firstly, the opinions were collected based on the professional's experience, and they relied too much on people's subjective judgements. Although the subjectivity has been seen as a common problem in questionnaire survey, it still limits the accuracy of the findings. Secondly, cautions should be warranted because of the small sample size. Thirdly, it should be noted that, in some cases, the long-term impacts of PPP projects could not be seen at the moment until the closure of the project life cycle.

Project success measures are extremely important for stakeholders to evaluate the effects of PPP projects. The performance and success of a PPP project could not be intuitively demonstrated without explicit measures of PPP project success. Future studies would explore the dependent relationships between critical success factors and PPP project success indicators.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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Research Article

Network Planning Method for Capacitated Metro-Based Underground Logistics System

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Underground logistics system (ULS) tends to alleviate traffic congestion, increase city logistics efficiency, mitigate the negative effects of traditional logistics processes, and improve the sustainability of urban areas. However, the relatively high cost and risk of underground construction are serious obstacles to implementing ULS. Integrating ULS into modern metro system (M-ULS) is considered to be feasible and efficient to solve this problem. This paper aims at developing a metro system-based ULS network planning method. First, an evaluation model of underground freight volume was proposed considering service capacity, freight flow, and regional accessibility. Second, a set of mixed integer programming model was developed to solve the problem of optimal nodes' location-allocation (LAP) in the network. Then, a hybrid algorithm was designed with a combination of E-TOPSIS, exact algorithm, and heuristic algorithm. Finally, two lines of Nanjing Metro were selected as a case to validate the proposed planning method. The results showed that the new system can significantly reduce the construction costs of ULS and alleviate traffic congestion. Moreover, the potential of metro stations and underground tunnels can be fully exploited to achieve higher logistics benefits.

1. Introduction

Traffic congestion is one of the "dilemmas" encountered by metropolises around the world. The fifth type of transportation and supply system, "underground logistics system" (ULS), has been developed to address the energy consumption, environmental pollution, and safety issues [1]. Various forms of ULS with different locomotives or driving methods have been developed and applied, such as *CargoCap* underground freight transportation system in Germany [2], *OLS-ASH* project in Netherland [3], and *Pipe§net* vacuum freight capsule in Italy [4–7]. ULS is widely recognized as a great innovation in the logistics industry because of its huge benefits to the city. It can quickly transport goods through underground pipes or tunnels within cities or between cities [8, 9]. However, it is undeniable that the high cost, long construction period, and high-risk of underground projects [10–12] are serious obstacles to ULS development. Reducing the construction cost is critical to improve the uptake of ULS [13].

Dampier and Marinov proposed a new conception of "integrating underground freight transport into modern metro system" (metro-based ULS, designated as M-ULS), which offered a feasible way with limited budget [14]. As a special form and promising alternative of ULS network, M-ULS has become one of the hottest research topics. Especially, setting up the intermodal network aims at maximizing the efficiency of cargo transport without interfering with the passenger transport system. The organizational process of this new system is complicated. It involves the linkage and optimization of the dual objectives of the passenger and cargo transportation system. The cargo needs to be sent to the demand points via reasonable metro stations and the distribution system on the ground. Therefore, the global optimization of the M-ULS efficiency can be classified as a special type of capacitated multistage facility location problem (CMFLP). The aim of this paper is thus to design a multilevel node location-allocation solution for M-ULS through mathematical modeling and simulation.

Research on ULS has been ongoing for nearly 30 years, but M-ULS is still an emerging area. Existing studies verified the feasibility of M-ULS and proposed concept designs. M-ULS is defined as an intermodal mechanism of mixed passengers and freight, in which batch driving or attachment carriages are enabled by utilizing metro railways [15]. Their advantage not only lies on the reservation of traditional ULS benefits in alleviating traffic congestion, improving urban environment and freight efficiency, but also contributes to a huge saving of the underground space, reducing construction costs and period. The passenger transport efficiency would not be interfered through rational technology design and operation management [15]. In Tokyo, new subway-integrated ULS received public endorsement in a pilot project [16]. In Newcastle upon Tyne, metro network was used for the collection of small-sized to medium-sized parcels, low-density high-value goods, and recyclable material [17]. In Korea, the freight volume of Seoul Metro 50 platforms was predicted to validate the reduction of social cost and environmental problem [18]. Toronto subway has also been evaluated on how such a modal shift appealed to cargo shippers [19]. All in all, real-world simulations were widely developed in recent years [20–22].

However, few articles with the topics on the planning method of M-ULS network have been published. Hörl et al. and Masson et al. conducted qualitative analyses of node location problem of single-line metro freight transport [23, 24]. Fangting et al. proposed a location-routing model of multiline transfer problem of M-ULS [25], which aimed at minimizing delivery time to improve the efficiency of metro freight. The optimization of the single-layer network topology was carried out; however, the influence of urban freight flow distribution on the system service level was not involved. Ambrosino and Scutella [26] proposed a four-level complex network distribution structure including facility location, warehousing, transshipment, and strategic decisions. The findings have contribution for analyzing the CMFLP of M-ULS, although it does not directly discuss M-ULS. M-ULS itself is a complex system. Functional classification of different types of facilities is necessary to meet the needs of intermodal transport. In order to pursue higher logistics benefits, a systematic evaluation of the urban freight transport demand is required due to strict capacity constraints of M-ULS. The freight flow direction and node location are two key indicators of M-ULS network layout. Thereby, this paper proposed a hierarchical mixed integer programming model (MIPM) combined with comprehensive evaluation that could reflect the different relationships of nodes. Compared to the modeling benchmark of general facility location problem [27–29], three additional important factors had been considered: (i) *Constraint of metro network*. Compared to the traditional logistics LAP model, M-ULS distribution path, which is restricted by the existing metro network, cannot be freely selected and adjusted immediately. (ii) *New system service area*. The definition of new system service objects has to be integrated into the optimization process because maximizing the limited system service capability is a key to M-ULS planning. (iii) *Mixed transport organization is complicated*. The design principle of existing metro network is passenger oriented, and the passenger transportation efficiency cannot be influenced by the new system. Improving the service performance of the new system requires redesigning an organizational process of passenger and freight mixed transportation, and the global optimization of freight transportation process.

The contributions of this study mainly lie in three aspects: (1) an effective organizational planning method for M-ULS was proposed; (2) a mixed integer programming model with multiple constraints was developed to solve the capacitated metro-based underground logistics system location-allocation problem (CM-ULSLAP); (3) a hybrid heuristic algorithm was developed for the simulation of real-world. Two lines of Nanjing Metro were selected as a case to validate the proposed planning method. The findings can promote the implementation of ULS. In addition, this study offers new ideas and quantitative optimization approaches for linear or network-based complex engineering projects. The supplied case study provides additional insights for research and practices.

2. Problem Description

The CM-ULSLAP can be described as follows: there are m operating metro lines, n urban distribution centers (designated as UDCs), and k demand points. Firstly, cargo from the open UDCs which provide ULS services is imported into underground network through the nearby metro stations (designated as ULS terminal). Then, dedicated cargo trains travel between ULS terminals and different underground depots (designated as UDs). Those UDs refer to the retrofitted metro stations, in which UD-oriented trains are bypassed to the parallel freight platforms before entering the passenger platforms. In this process, the frequency of freight fleet keeps interlaced with metro, and existing transfer points can be activated as underground hubs (designated as UHs) to support underground transshipment. Finally, freight units floating up from UDs are allocated to the corresponding ground terminals (designated as GTs) by ground electric vehicles. Cargo is delivered to the customers who are within the service scope of M-ULS after automated sorting and packaging at GTs. The reversed procedures are presented in mirror image. Figure 1 demonstrates the organizational breakdown structures with planning issues of M-ULS.

The initial data that can be used for the metro freight planning usually focus on several incomplete customers characteristics, such as location, regular delivery route, and handover period record. Other important input data are the demand for travel, which is commonly formulated as the origin-destination (OD) matrix [30]. The freight OD matrix in this study is extracted based on the counts of travels multiplied by order capacity from one area to another. On this basis, the alternative solution aims to improve the current customer service with low cost and high efficiency. The high efficiency of M-ULS depends on the coordination of its own technical integration and freight flow distribution. In order to get this, the joint freight function should not lead

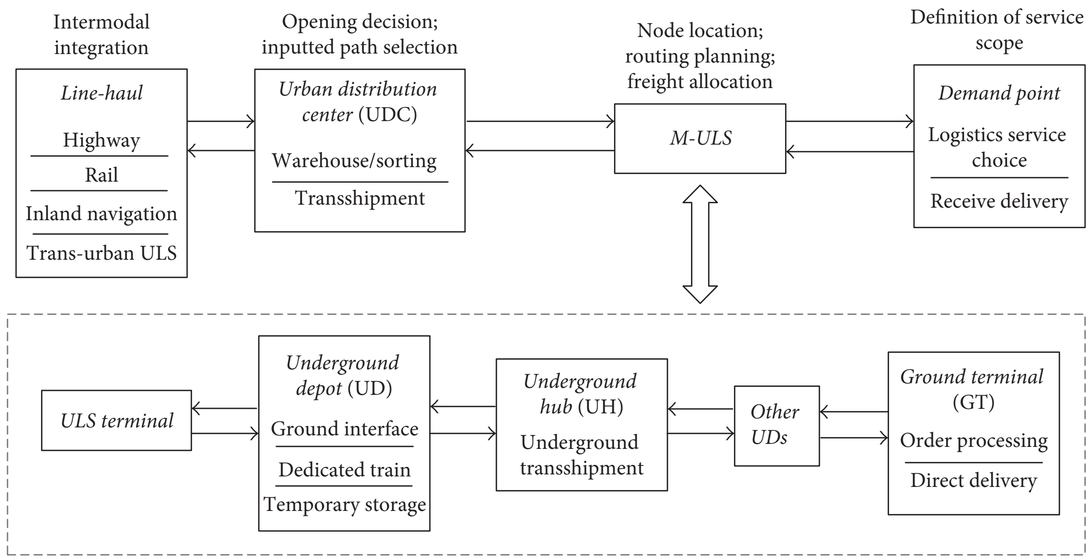

Figure 1: Operational modules and issues of M-ULS-integrated urban logistics.

to any degradation or disruption of passenger service [15]. As a result, goods and passengers must be separated. Meanwhile, the efficiency loss caused by intermodal transport can also be compensated by a highly integrated urban logistics benchmark. Taking into account the regional development density and spatial impact on the surrounding environment, in M-ULS, freight flows cannot be detained too much after reaching corresponding underground destinations. Instead, they should be transferred directly to the newly built ground terminals for processing. By setting such a transit layer between customers and underground distribution network, the transport efficiency and system service capacity can be largely improved by dividing the M-ULS from the traditional logistics systems. Based on the planning principles discussed above, the node facilities are divided into the following four layers:

2.1. ULS Terminal. The ULS terminal plays a role in docking UDC with underground network. The freight units which have been well sorted and packed in UDC will be simply coded at the ULS terminal to each exact ground terminal or underground depot. In this paper, the location of the ULS terminal was determined by calculating the weighted distance to nearby urban distribution centers.

2.2. Underground Depot (UD). The UD is defined as an enhanced metro station which has the function of cargo handling and connects the underground logistics network with upper ground terminals. The number and distribution of UD directly affect the system service. In this paper, a MILP method with corresponding heuristic algorithm was introduced to search the optimal location-allocation of UD-GT.

2.3. Ground Terminal (GT). GT is one of the optimization targets, which is affiliated with UD. GT is also a key part of the entire M-ULS supply chain because it is directly oriented to customers whose delivery requirements are time efficient. The cargo handling capacity of GT is the major handicap in the performance of system service. In this paper, the location of ground terminal was transformed into the capacitated set covering problem (CSCP). And a set coverage model for GT location is established.

2.4. Demand Point. Demand point is also one of the optimization targets. Because of the limited transportation capacity of the metro system which is far from meeting cargo supply for all customers, a screening evaluation of demand points is essential for maximizing logistics benefits and service scope.

In order to simplify the study, the following assumptions for CM-ULSLAP are proposed: (1) suburban UDC reasonably allocates goods into the underground network, and the freight handling capacity of ULS terminal is unlimited; (2) each candidate GT can only correspond to one UD, and the source of freight flows is unique; (3) taking a full carriage of dedicated trains as a freight unit, the less than truckload (LTL) transportation are not allowed in the underground distribution network; (4) the processing time and transfer cost at underground hub are not considered, and all UHs are activated by default; (5) intermodal transport does not involve the urban road network layout and additional expenses caused by traffic congestion; (6) M-ULS does not reschedule the original timetable of metro system, but underground freight flow frequency can be adjusted based on the traffic volume of passengers; (7) construction and storage condition at UD are not considered; and (8) only part of customers' attributes are available.

3. E-TOPSIS for Evaluation of Underground Freight Volume

The entropy weighted TOPSIS method (E-TOPSIS) is applied in the weighting process of the evaluation indicator system [31]. The information entropy calculated in the indicator matrix is used to weight the dispersion degree of demand characteristics, all that can avoid the influence of human subjective factors [32]. The final points of the evaluation objects in multiobjective decision-making are gotten by the TOPSIS method which can solve the higher requirement for the sample.

This paper used unity of freight flows (UFFs), regional accessibility (RA), and source distance (SD) as three dimensions to reflect UDC's preference for the characteristics of customers' demand. Therein, variables UFF and RA were obtained from Nathanail et al. [33], who maintained that the urban traffic alleviation and the development of integrated transport to reduce the scattered freight delivery were two of the most remarkable characteristics of the sustainable city logistics. In our study, we took these two quantitative features as the functional requirements of the metro freight system, where UFF was formulated as the accumulated OD from different directions according to Masson et al. [24] and RA was formulated as the accumulated delivery period from different directions divided by average path length according to Montoya-Torres et al. [34]. SD was formulated as a variable that supplemented UFF with distance influence, which involved the data of spatial distance and freight OD from different directions. These 3 variables share the initial data mentioned above.

(i) Unity of freight flows. Since UD does not have the function of parcel disassembly, logistics benefits are promoted along with the growth of underground mileages [35]. Therefore, M-ULS should provide centralized supplies as much as possible to areas with huge demand:

$$x_{1j} = \overline{Q_j}, \tag{1}$$

where Q is the total amount of freight picked up and delivered per day at demand point j.

(ii) Regional accessibility. The efficiency of urban logistics is largely influenced by traffic congestion [36–38]. By removing goods from above to underground, the freight mobility of some regions with poor accessibility can be effectively improved [39]. The index of regional accessibility can be characterized by the time-road response function:

$$x_{2j} = \sum_{i=1}^{m} \left(\frac{t_{ij}}{S} \right)^{\tau_{ij}}, \tag{2}$$

where t_{ij} is the average delivery time form UDC i to demand point j, S is the length of the delivery route, and $\tau_{ij} \in (0,1)$ is the time sensitive factor.

(iii) Source distance. Underground logistics can generate considerable internal and external benefits [40]. M-ULS should take full advantage of the length of metro lines. Putting goods which are far from the source (ULS terminal) but in huge demand into the system will lead to the overall increase of logistics values. The source distance index can be portrayed as

$$x_{3j} = \sum_{i=1}^{m} \left\| d_{ij} \right\| \cdot \left[\gamma_i \left(x_j \right) \right]^{\alpha_j}, \tag{3}$$

where $\|d_{ij}\|$ is the Euclidean distance between UDC i and demand point j, $\gamma_i(x_j)$ is the freight correction factor of the sample, which represents the proportion of the freight volume from direction i, and α_j is an amplification coefficient.

An evaluation model for the priority level of M-ULS service is constructed.

(1) The initial decision matrix. Assuming there are m evaluation indicators and evaluation indicator sets have n subsets, the evaluation value of indicator i in subset j is x_{ij}. The decision matrix of all subsets is

$$R = \left(x_{ij} \right)_{m\times n} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}. \tag{4}$$

(2) Standardization of the decision matrix. In order to solve the uniform of indicators' units, this paper makes the standardization on all indicators. Take the best value of indicator i as x_i^{best}, the worst as x_i^{worst}. The efficacy coefficient α is introduced to obtain the normalized data matrix B:

$$B = \left[x_{ij} \right]' = \frac{x_{ij} - x_i^{\text{worst}}}{x_i^{\text{best}} - x_i^{\text{worst}}} \cdot \alpha + (1-\alpha), \quad \alpha \in (0,1). \tag{5}$$

(3) Determine the indicators weight. The indicator weights are determined by the expert evaluation method in the TOPSIS. The results are quite subjective. Therefore, this paper adopts the information entropy method to determine the indicators weight.

e_i denotes the entropy of indicator i in the standardized decision matrix:

$$\begin{gathered} T_{ij} = \sum_{k=1}^{l} \left(\frac{x_{ij}}{\sum_{j=1}^{n} x_{ijk}} \right), \\ e_i = h \cdot \sum_{j=1}^{n} T_{ij} \ln \left(T_{ij} \right), \quad \forall i = 1, 2, \ldots, m, \\ h = \frac{1}{\ln n}, \quad 0 \le e_i \le 1. \quad \text{If} \quad T_{ij} = 0, \quad T_{ij} \ln \left(T_{ij} \right) = 0. \end{gathered} \tag{6}$$

The dispersity of the evaluation value of indicator i can be represented as follows:

$$\beta_i = 1 - e_i, \quad \forall i = 1, 2, \ldots, m. \tag{7}$$

If T_{ij} is more dispersed, β_i is bigger and indicator i is more important. If T_{ij} is relatively concentrated, indicator i is less important. If all T_{ij} are equal and the distribution is absolutely concentrated, indicator i is invalid. So, the weight factor of nonsubjective preference for indicator i is

$$Y = (y_1, y_2, \ldots, y_m)^T,$$
$$\forall y_i = \frac{\beta_i}{\sum_{i=1}^{m} \beta_i}. \tag{8}$$

(4) The weighted matrix of indicators' value. According to the normalized data matrix B and the obtained entropy weight y_i, the weighted matrix of indicators' value is calculated by following formula:

$$K = Y \cdot \begin{bmatrix} T_{11} & \cdots & T_{1n} \\ \vdots & \ddots & \vdots \\ T_{m1} & \cdots & T_{mn} \end{bmatrix} = \begin{bmatrix} k_{11} & \cdots & k_{1n} \\ \vdots & \ddots & \vdots \\ k_{m1} & \cdots & k_{mn} \end{bmatrix}. \tag{9}$$

(5) Calculating the relative distance. The selection scheme of candidate GT for this phase is calculated with the relative proximity ρ_j of positive and negative ideal solutions under weighted matrix K:

$$d_j^+ = \left[\sum_{i=1}^{m} y_i \sum_{k=1}^{l} \left(k_{ij} - x_i^+ \right)^2 \right]^{1/2}, \quad \forall j = 1, 2, \ldots, n. \tag{10}$$

where d_j^- denotes the Euclidean distance between k_{ij} and negative ideal solution:

$$d_j^- = \left[\sum_{i=1}^{m} y_i \sum_{k=1}^{l} \left(k_{ij} - x_i^- \right)^2 \right]^{1/2}, \quad \forall j = 1, 2, \ldots, n,$$
$$\rho_j = \frac{d_j^-}{\left(d_j^+ + d_j^- \right)}. \tag{11}$$

For the candidate location scheme, ρ_j is generally between 0 and 1. The closer to 1, the more appropriate the corresponding scheme. Finally, demand points in the newly built GT are selected to accept the M-ULS service according to the value of ρ_j listing in descending order, until one of the nodes or underground sections is overloaded. Underground freight OD can be uniformly formulated as

$$\overline{Q} = Q_i^x \cdot A_j,$$
$$\forall A_j = \begin{cases} (1, 1, \ldots, 1)^T, & 1 \geq \rho_j \geq \overline{\rho}_j, \\ (0, 0, \ldots, 0)^T, & 0 \leq \rho_j \leq \overline{\rho}_j. \end{cases} \tag{12}$$

4. Multistage Node Location Model for M-ULS

4.1. Parameter Definition

(1) Define V_C, V_S, and V_P as sets of metro station, candidate UD, and GT, respectively.

The cost parameters: c_1, integrated unit price for underground transport; $c_2 = \beta \cdot c_1$, comprehensive price of ground transport, β is the freight price coefficient, which reflects the pricing gap between two modes; and c_3, construction cost of UD (depreciated to daily).

The distance parameters: d_{ij}, the distance between UDC j and metro station i; r_{ik}, the shortest path for goods routed to the UD k, in which underground transfer is included; and Z_x, andZ_i, coordinates of GT and metro station.

The freight parameters: Q_{ij}, the amount of goods sent by UDC j to certain metro line where the UD i is located; Q_k, the amount of goods picked up by the UD k per day; $u_{\max}^j$, capacity of metro line j.

(2) Decision variables.

M_i: 1, if metro station i is selected as UD; 0, otherwise.

P_{xk}: 1, if GT x is visited by the vehicles from UD k; 0, otherwise.

H_{ij}: 1, if metro station i is selected as underground access of goods from UDC j; 0, otherwise.

4.2. Set Coverage Model for Ground Terminal. Sets $A(j)$ of all demand points covered by ground terminal a_j and sets $B(i)$ of all GTs that cover demand point b_i are given. Let Y_{ij} be the distribution coefficient of cargo throughput for a_j to b_i and X_j be the decision of whether to locate ground terminal at a_j:

$$\min \sum_{j, a_j \in V_R^*} X_j. \tag{13}$$

subject to

$$L(i, j) \leq d, \quad \forall b_i \in A(j); a_j \in B(i), \tag{14}$$

$$\sum_{i, b_i \in A(j)} \overline{Q_i} Y_{ij} \leq Q_j^{\max} X_j, \tag{15}$$

$$\sum_{j, a_j \in B(i)} Y_{ij} = 1, \quad \forall b_i \in V_R^*, \tag{16}$$

$$X_j \in \{0, 1\}, \quad \forall a_j \in B(i). \tag{17}$$

The objective (14) is to search the minimum number of GT under the current demand scenario; constraints (15) and (16) indicate the maximum service scope and cargo handling capacity of the ground terminal; and constraint (17) specifies the sum of freight demand b_i shared by each GT should be equal to the amount of OD obtained in (13).

For unified presentation, the above model is written in the form of matrix inequality:

$$
\begin{array}{c}
\begin{array}{cccc}
\multicolumn{4}{c}{\cdots\ N\ \text{dimension}\ \cdots} & \multicolumn{4}{c}{\cdots\ N\ \text{dimension}\ \cdots} & \multicolumn{4}{c}{\cdots\ N\ \text{dimension}\ \cdots} & & \multicolumn{4}{c}{\cdots\ N\ \text{dimension}\ \cdots}
\end{array}\\
K=\left[\begin{array}{cccccccccccccccccc}
0 & 0 & \cdots & 0 & D_{11} & 0 & \cdots & 0 & D_{12} & 0 & \cdots & 0 & \cdots & D_{1n} & 0 & \cdots & 0\\
0 & 0 & \cdots & 0 & 0 & D_{21} & \cdots & 0 & 0 & D_{22} & \cdots & 0 & \cdots & 0 & D_{2n} & \cdots & 0\\
\vdots & \ddots & \cdots & \vdots & \vdots & \ddots & \cdots & \vdots & \vdots & \ddots & \cdots & \vdots & \cdots & \vdots & \ddots & \cdots & \vdots\\
0 & 0 & \cdots & 0 & 0 & 0 & \cdots & D_{n1} & 0 & 0 & \cdots & D_{n2} & \cdots & 0 & 0 & \cdots & D_{nn}\\
-Q^{j}_{\max} & 0 & \cdots & 0 & D_{11}\overline{Q_1} & D_{21}\overline{Q_2} & \cdots & D_{n1}\overline{Q_n} & 0 & 0 & \cdots & 0 & \cdots & 0 & 0 & \cdots & 0\\
0 & -Q^{j}_{\max} & \cdots & 0 & 0 & 0 & \cdots & 0 & D_{12}\overline{Q_1} & D_{22}\overline{Q_2} & \cdots & D_{n2}\overline{Q_n} & \cdots & 0 & 0 & \cdots & 0\\
\vdots & \ddots & \cdots & \vdots & \vdots & \ddots & \cdots & \vdots & \vdots & \ddots & \cdots & \vdots & \cdots & \vdots & \ddots & \cdots & \vdots\\
0 & 0 & \cdots & -Q^{j}_{\max} & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & D_{1n}\overline{Q_1} & D_{2n}\overline{Q_2} & \cdots & D_{nn}\overline{Q_n}
\end{array}\right]
\begin{array}{l}
\left.\begin{array}{c}\\ \\ \\ \\ \end{array}\right\} N\\
\left.\begin{array}{c}\\ \\ \\ \\ \end{array}\right\} N
\end{array}
\end{array}
$$

$$Z=\{X_1,\ldots,X_n,Y_{11},\ldots,Y_{n1},Y_{12},\ldots,Y_{n2},\ldots,Y_{1n},\ldots,Y_{nn}\}^T,$$

$$b=\{-1,\ldots,-1,0,\ldots,0\}^T. \tag{18}$$

K is a $2n * n(n+1)$ dimensional matrix. In the first n line, elements of column 1 to n equal 0; $n+1$ to $2n$ is a diagonal matrix with principal diagonal $D_{11},\ldots,D_{n1}$, and so forth. In the line $n+1$, column 1 to n principal diagonal is $-Q^{j}_{\max}$, while column $n+1$ to $2n^2$ has a single line element $D_{11}\overline{Q_1},\ldots,D_{n1}\overline{Q_n}$, and so forth.

Z is a $n+n^2$ dimensional vector. b is $2n$ in length, of which elements in the first n line equal -1, otherwise 0. All solutions of Z satisfying $K\cdot Z\le b$, $0\le Y_{ij}\le 1$, $i,j\in V^{*}_{R}$ at the same time compose the feasible space of the GT location under the maximum service capability.

4.3. Location-Allocation Model for Underground Depot.

$$\min\quad J_b=\sum_{i\in V_C}\sum_{k\in V_S}\sum_{x\in V_P}M_iP_{xk}Q_x\left\|Z_x-Z_i\right\|c_1+\sum_{i\in V_C}M_ic_3 + \sum_{i\in V_C}\sum_{j=1}^{m}\sum_{k\in V_S}H_{ij}\left(d_{ij}Q_{ij}\beta+r_{ik}Q_k\right)c_1, \tag{19}$$

subject to

$$Q_k\le Q^{k}_{\max},\quad \forall k\in V_S \tag{20}$$

$$\sum_{j=1}^{m}\sum_{i\in V_C}H_{ij}Q_{ij}+\sum_{x=1}^{q}\left(\sum_{k=x+1}^{y-1}H_{ij}Q_{xk}\right)\le u_{\max},\quad \forall q\in\{0,1,\ldots,m-1\}, \tag{21}$$

$$\sum_{i\in V^{n}_{C}}H_{ij}=1,\sum_{j=1}^{m}H_{ij}\ge 1, \tag{22}$$

$$\sum_{k\in V_S}P_{xk}=1,\sum_{x\in V_P}P_{xk}\ge 1,\forall x\in V_P,k\in V_S, \tag{23}$$

$$\sum_{i\in V_C}M_i=y, \tag{24}$$

$$M_i\in\{0,1\},\quad \forall i\in V_C, \tag{25}$$

$$P_{xk}\in\{0,1\},\quad \forall x\in V_P,\quad k\in V_S, \tag{26}$$

$$H_{ij}\in\{0,1\},\quad \forall i\in V_C,\quad j\in\{1,2,\ldots,m\}, \tag{27}$$

Formula (20) is the objective function, which consists of transportation cost and node construction cost for the intermodal logistics system. Constraint (21) reflects the capacity restrictions of underground freight handling at UD; constraint (22) ensures that the capacity of metro lines are not violated; constraint (23) stipulates that the ULS terminal on a single metro line is unique, but the UDC can be assigned to different ULS terminals based on reality; constraint (24) guarantees that UD is connected to at least one ground terminal of which ownership is unique; constraint (25) specifies that the number of metro stations that are selected as underground depots equals y; and constraints (26)–(28) are the range of relevant decision variables.

5. Solution Method

CM-ULSLAP is an NP-hard problem in which the customer layer (demand point), middle layer (GT), underground logistics layers (UD and UH), and supply layer (UDC) are integrated into a complex intermodal network. This problem is computationally intractable due to the following reasons. First, there is not a single layer of node information that can be fully invoked. Different intermodal strategies result in the conflict between customer demands and economic considerations. The evaluation procedure is hard to carry out. On the contrary, the possible paths for each OD pairs are so huge that it is computationally expensive and unsustainable to enumerate all of them for each configuration involving transport mode choice and corresponding routing transfer. Once the supply relationship and the generation strategy of candidate GT are determined, CM-ULSLAP reduces to the bi-level capacitated intermodal network design problem (BCIND). For calculation efficiency and stability, the access routes from UDCs to ULS terminals were determined in advance to cut off the supply layer. Then the entropy weighted TOPSIS method (E-TOPSIS) was applied to evaluate the demand characteristics in model (P1). Next, an exact algorithm for set coverage model is served for obtaining feasible solutions in model (P2), thereby cutting off the customer layer by replacing abundant demand points with candidate GT sets. Immune Clone Selection Algorithm (ICSA) was applied to optimize the location of UD and allocation of deterministic GT which following the minimum objective cost in model (P3). An adaptive mechanism of underground route navigation was also embedded in ICSA where fleet flows always follow the shortest path that is currently available until the certain section is blocked. Finally, the solution space of combined models has been reduced from five dimensions $M*N*K*|V_C|*|V_P|$ to three dimensions $M*|V_C|*|V_P''|$ which contributes a lot to the computational efficiency. The relationships and decomposition of models are shown in Figure 2.

The ICSA was inspired by the principle of clonal selection of antibodies in the biological immune system [41]. It was used to explain the basic characteristics of adaptive immune response to antigen stimulation. The ICSA has been widely used in solving problems such as combinatorial optimization, intelligent optimization, and production scheduling due to its powerful data search capabilities [42–44]. However, the convergence rate of original ICSA is slower, immune probability and cloning probability are relatively fixed, and the degree of change is relatively low when solving complex problems. In this paper, we introduced a self-adaptive mutation operation based on normal distribution to achieve a uniform and dynamic global high-level ambiguity for each antibody that meets the mutation rate for the characteristics of multiple UD feasible solutions and frequent information feedback at each stage. Probability variation enhances the randomness and stability of the search and can effectively prevent the solution from falling into local optimum. The main operation of the heuristic algorithm is shown in Figure 3.

The solution steps of GT location are listed in Algorithm 1.

Step 1: Generate Initial Population. The initial antibodies were obtained from the memory cells that were generated randomly from the feasible solution space. The coding of antibodies includes the UD open strategies and the location information of newly built GT which were fed back by E-TOPSIS. The initial antibody population was recorded as $P_0(\mathrm{RC})$, which was composed by RC number randomly generated antibodies.

Step 2: Diversity Evaluation. Select k individuals with the highest fitness value and t individuals with the lowest affinity from the parent population $P_n(\mathrm{RC})$ to compose the solution vector, where $k = \mathrm{RC} \times 20\%$ and $t = \mathrm{RC} \times 10\%$. Affinity was used to indicate the matching degree between antibody and antigen, namely, the optimal satisfaction between the candidate GT sets and open UD in objective (19). Lehmer mean [45] was recommended to the affinity determination. The affinity of the uth solution vector can be described as

$$I_u = \frac{1}{1 + L(u, v)}; \forall L(u, v) = \frac{\sum_{u \neq v} \left\| J_b(u) - J_b(v) \right\|^2}{\sum_{u \neq v} \left\| J_b(u) - J_b(v) \right\|}. \quad (28)$$

Step 3: Clone Operation. The clone ratio was calculated by the evaluation of affinity and similarity between antigen and other antibodies. The cloned population $Z_n(N_C)$ is produced by replicating $k + t \pm d$ number of selected antibodies. Specifically, the total number of clones generated for all selected antibodies is

$$N_{\mathrm{RC}} = \sum_{u=1}^{k+t\pm d} \mathrm{round}\left(\mathrm{RC}\left(1 - I_u\right)\right). \quad (29)$$

Step 4: Gene Mutation. Select a group of clones from $Z_n(N_{\mathrm{RC}})$ and perform Gaussian mutation on them to obtain population S_n. The mutation rate adopts an adaptive strategy [46] which is related to the adaptation value f_k of the antibody. This mutation operation can be described as $m_j = \mathrm{normrnd} \quad (m_j, \sigma, 1, 1)$, where m_j is the jth attribute of the clone, and normrnd is a normal-distribution random number with a mean of m_j and a standard deviation of σ. The σ domain of the antibody is adaptively adjusted to $\sigma = \omega \cdot I_u/f_k$ following its adaptation value and affinity.

Step 5: Immune Selection. The memory population M is consisted of a batch of antibodies with the highest f_k from the set $S_n \cup Z_n$. Then select 30% k number of antibodies with the highest fitness value from M to update the equal number of antibodies with the lowest fitness value in the population P_n to form the progeny population P_{n+1}.

Step 6: Node Search Reset. After reaching the maximum number of iterations N, check $I_y^{(n+1)}(i)$, if i exists so that $I_y^{(n+1)}(i) > \max_{t \neq y} I_t^{(n+1)}$. Then update the objective cost $J_b(i)$. Let $y = y + 1$, returning to step 2; if not exists, step forward.

Step 7. The algorithm terminates when reaching iteration number N. Extract the most-affinity antibodies with their attributions as the preferred configuration of M-ULS.

6. Scenario Analysis

6.1. Background and Parameter Setting. The Nanjing city is located at latitude N32°02′ and longitude E118°46′ in East China. This city is situated on the Yangtze river bank. Based on the 2016 census, Nanjing had a population of 8.27 million. Express delivery volume of Nanjing had reached 630 million parcels in 2017 (ASKCI consulting). The total amount of social logistics is nearly 3 trillion RMB, with a 7.96% annual growth rate (Nanjing Municipal Bureau of Commerce). Three major transportation hubs, Nanjing Railway Station, Nanjing South Railway Station, and Lukou Airport, run through the city of which freight throughput capacity breaks 800,000 tons per year. Nowadays, there are 9 metro lines and 164 stations in Nanjing. The total length of metro lines is 347 kilometers, the 7th longest in the world.

For the sake of studying the performance of metro freight in the real-world case, Nanjing Metro was taken as a case to schedule the optimal configuration layout under minimum objective cost. A scenario of 2 open UDC, Line 1 and Line 2 with an activated UH and 31 stations, was

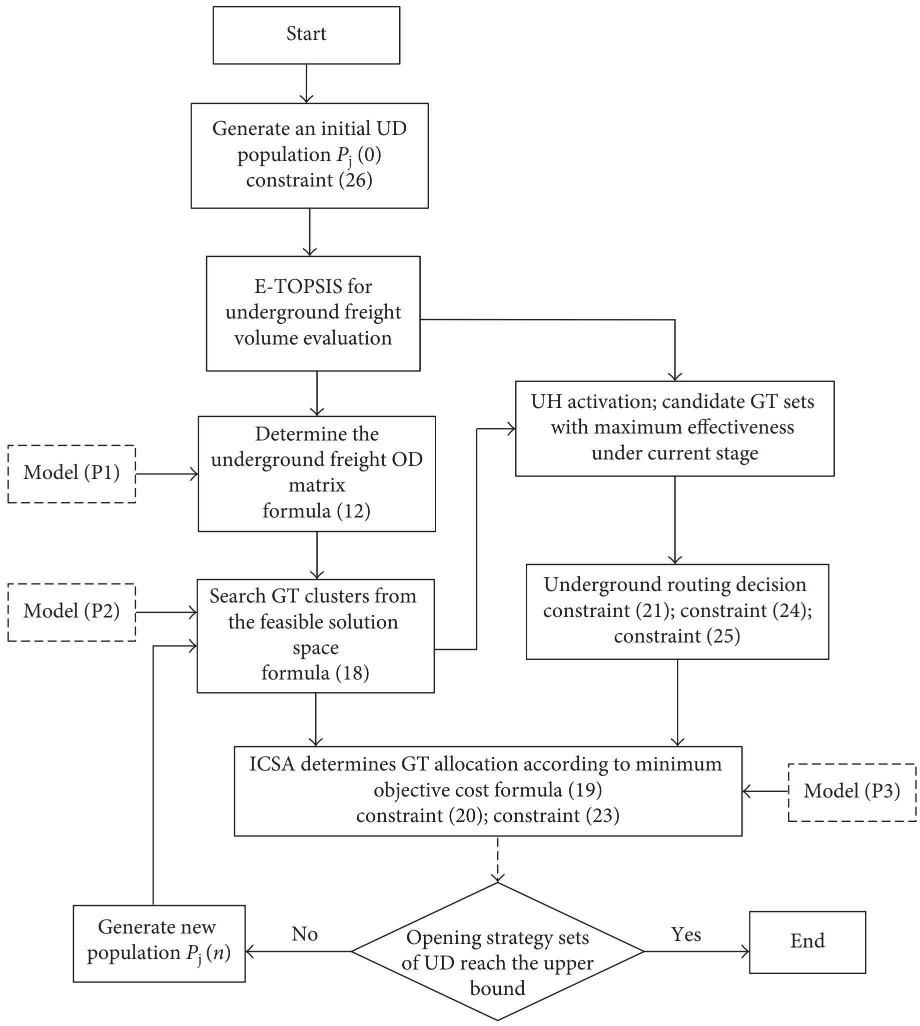

Figure 2: Relationships and decomposition of proposed models.

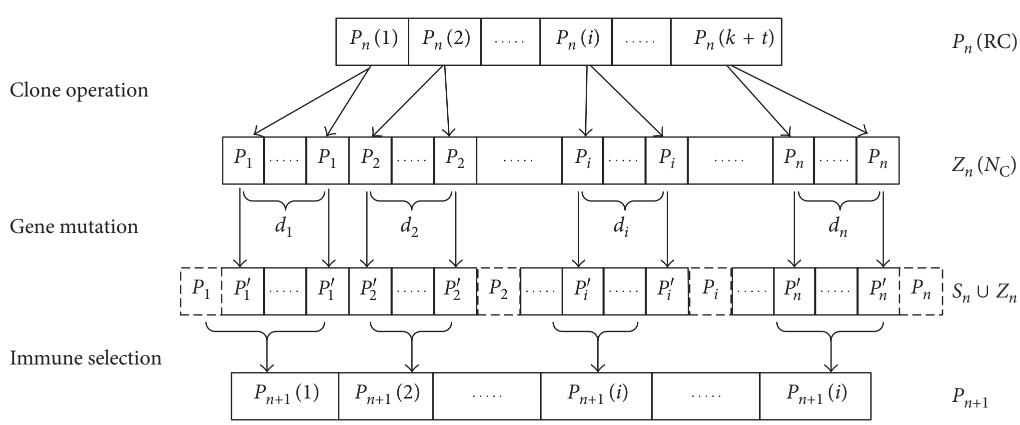

Figure 3: The process of ICSA.

involved based on the real-world location. As shown in Figure 4, there are 274 demand points distributed in a range of 201 square kilometers from *Xinjiekou* to *Nanjing South Railway Station*. Relevant data and parameter values were obtained by the Monte Carlo simulation method, as shown in Table 1. The underground freight volume of each UDC was limited to 10,000 tons per day to be in consistent with the transport capacity of underground tunnels. Cargos from two metro lines can be transferred at *Xinjiekou* Station where the function of UD is invalid.

(1) Initialization $X_j = 0$, $Y_{ij} = 0$, V_R^*
(2) clear $A(j)$, $B(i)$
(3) **while** $X_j = 0$ **do**
(4) **for** $j' \in V_R^*$, find $|A(j')| = \max\{|A(j)|\}$
(5) **if** true **then**
(6) let $X_{j'} = 1$, remove j' from V_R^*
(7) **end if**
(8) **end for**
(9) **for** $j \in A(j)$ **do**
(10) assign to j' subsequently according to length $B(i)$
(11) **while** $Q_{\max}^{j'} = 0$ or $A(j') = \varnothing$ **do**
(12) **end while**
(13) **for** $i \in A(j')$ and $Y_{ij} \leq 1$ **do**
(14) **if** $\overline{Q_i}(1 - Y_{ij}) \leq Q_{\max}^{j'}$ **then**
(15) let $Y_{ij'} = 1 - Y_{ij}$, $Q_{\max}^{j'} = Q_{\max}^{j'} - \overline{Q_i}(1 - Y_{ij})$, $Y_{ij} = 1$
(16) remove i from V_R^*
(17) **end if**
(18) **if** $\overline{Q_i}(1 - Y_{ij}) > Q_{\max}^{j'}$ then
(19) let $Y_{ij'} = Q_{\max}^{j'}/\overline{Q_i}$, $Y_{ij} = Y_{ij} + Y_{ij'}$, $Q_{\max}^{j'} = 0$
(20) **end if**
(21) check $V_R^* \neq \varnothing$
(22) **if** true **then**
(23) return to line 4
(24) **end if**
(25) **end while**

ALGORITHM 1: Set coverage model for ground terminal.

FIGURE 4: Sketch map of metro lines and demand areas.

Table 1: Parameters of metro freight.

Parameter	Value
Freight price coefficient, β	3
Travel cost on underground network	Uniform (1, 2)
Cost of retrofitting underground depot	Uniform (4000, 6000)
Capacity of underground depot	Uniform (3000, 4500)
Capacity of ground terminal	Uniform (2000, 3000)
Freight demand of customers	|Normal (50, 30)|
Travel time on ground delivery path	Uniform (20, 200)
Maximum service radius of ground terminal	Uniform (2, 3)

The proposed solution algorithm was coded in MATLAB R2016, and all experiments were run on a desktop computer with Windows 10, Intel Core I7-7700K 4.2 GHz processor, and 32 GB of RAM. The initial population size $p = 50$ and maximum iteration number $G_{\max} = 100$.

6.2. Simulation Results. The E-TOPSIS method was applied to illuminate the range of system services at first. The number of qualified demand points is reduced to 228, in which the relative proximity of the most urgent area $\max \rho_j$ equals 0.1916, and the critical proximity $\overline{\rho_j} = 0.1812$. Metro Line 1 saturates faster than the Line 2 with the cargo throughput of 9,747 tons per day and 7,758 tons per day, respectively. Algorithm 1 gave a set of feasible GT location demonstrated in Figure 5. The number of ground terminal that satisfies the constraints is determined as fifteen. Then the optimization results from ICSA indicate that the minimum cost of the M-ULS-integrated logistics system is 185,900 RMB per day, while the transport cost of traditional ground logistics is 198,700 RMB per day. UDs were selected to locate on the following six stations: *Xinmofanmalu*, *Andemen*, *Hanzhongmen*, *Daxinggong*, *Minggugong*, and *Jiqingmendajie*. Figure 6 depicts the optimal open strategy of UD and corresponding allocation. *Minggugong* Station captured the busiest UD, with the daily freight volume of 3914.9 tons, whereas *Andemen* Station had the lowest freight volume of 1483.9 tons with single affiliated GT. The specific node information is shown in Table 2.

Table 3 depicts the comparison of traffic volume from 2 UDCs to 15 GTs under traditional point-to-point distribution mode and M-ULS, where traffic volume (TV) is defined as freight OD quantity multiplied by the transport distance [47]. It can be seen that the ground traffic volume (GTV) of GT-4 has been reduced by 69.32%, which benefits the most from underground logistics. Most GTVs got a different degree of alleviation between 30% and 65%. Note that GT-15 in Figure 5 is relatively close to the freight sources, and the GTV has increased by 36.71% after adopting M-ULS. Therefore, the traditional point-to-point model is more economical for nodes near such UDCs.

When it came to the underground traffic volume (UTV) in M-ULS, all GTs exceeded 50% of the underground logistics ratio, where the maximum reaching 75.71% at GT-5. The average above and underground mileage at *Xinmofanmalu* accounted for 34.03% and 65.97%, respectively. Table 4 demonstrates the overall variation of traffic volume. Benefit from the higher utilization of underground

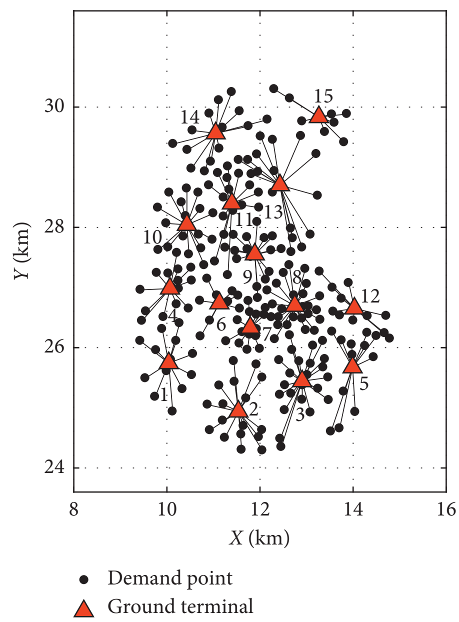

Figure 5: Service scope of M-ULS and GT location.

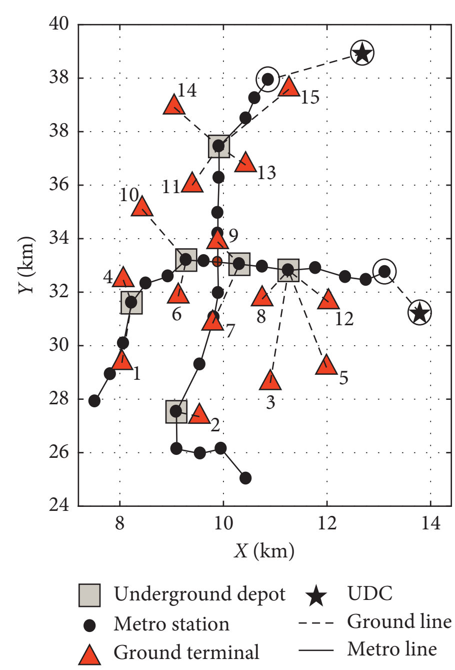

Figure 6: Optimal location-allocation of UD.

distribution, less than half of the ground delivery is required. For this part of goods that need to be delivered to the downtown areas, the original long-distance highway travel is decomposed into several subtransport processes above and underground. As a result, fewer freight vehicles are needed. The mobility on urban traffic loops will be significantly improved and some congested road sections will be effectively alleviated from traffic pressure.

6.3. Sensitivity Analysis. Figure 7 indicates the variation of optimal cost with freight price coefficient β and number of

Table 2: Summary of optimal node information.

Open UD	Freight volume (t)	Number of GT allocation	Service radius (km)	Source freight (t) (UDC 1, UDC 2)	Travel distance above (km)	Travel distance underground (km)
Xinmofanmalu	3583.5	11	2.99	(642.3, 346.6)	10.83	16.56
		13	2.86	(730.6, 328.1)	9.86	16.56
		14	2.84	(664.5, 358.6)	12.17	16.56
		15	2.66	(360.2, 154.2)	14.93	16.56
Andemen	1483.9	2	2.18	(970.1, 513.8)	9.19	28.64
Hanzhongmen	2774.3	6	1.70	(756.2, 568.8)	9.76	19.79
		10	1.92	(717.8, 731.5)	12.66	19.79
Daxinggong	2925.9	7	1.41	(855.8, 628.7)	12.07	16.54
		9	1.83	(730.2, 711.2)	9.63	16.54
Minggugong	3914.9	3	2.95	(856.5, 513.2)	15.54	16.56
		5	2.91	(255.3, 315.5)	11.28	16.56
		8	1.75	(694.4, 765.3)	10.27	16.56
		12	2.41	(196.5, 318.2)	11.48	16.56
Jiqingmendajie	2822.5	1	2.03	(622, 793.9)	11.53	26.94
		4	2.01	(696.3, 710.3)	8.83	26.94

Table 3: Comparison of traffic volume between point-to-point mode and M-ULS.

Open UD	GT allocation	GTV in point-to-point distribution (ton·km)	GTV in M-ULS (ton·km)	UTV in M-ULS (ton·km)	GTV alleviation rate	Underground logistics ratio (%)
Xinmofanmalu	11	5159.7	2853.7	3453.8	−44.69%	59.48
	13	4220.2	2847.4	3513.7	−32.53%	59.06
	14	5632.0	3292.4	3572.7	−41.54%	70.03
	15	1496.3	2045.7	1685.2	+36.71%	75.31
Andemen	2	10530.6	3683.3	10624.3	−65.02%	62.68
Hanzhongmen	6	8134.4	3345.0	6557.2	−58.88%	66.97
	10	9466.0	4578.8	7172.3	−51.63%	51.59
Daxinggong	7	8466.9	4614.0	6260.6	−45.51%	60.99
	9	7230.1	3481.8	5976.0	−51.84%	63.20
Minggugong	3	7584.0	5525.3	6243.7	−27.15%	57.64
	5	2296.8	2115.6	2261.8	−7.89%	75.71
	8	6532.2	3705.5	5923.6	−43.27%	57.81
	12	1634.2	1404.4	1927.2	−14.06%	61.72
Jiqingmendajie	1	10860.7	3979.8	9535.0	−63.36%	60.46
	4	10097.0	3098.2	9472.5	−69.32%	52.59

Table 4: Overall variation of traffic volume.

	Overall GTV alleviation rate	Overall UTV ratio	Overall GTV ratio
Point-to-point mode M-ULS	0 49.09%	0 62.47%	100% 37.53%

UD-opened n_c. Note that the total cost of the intermodal system dropped slightly along with the increase of β and then reached the same level with traditional ground logistics when β equaled 2.52. Accordingly, there is a wide range of pricing options for underground freight transport, but the ratio of the discreet unit price of M-ULS to traditional ground logistics should be less than 1 : 2.5 in order to achieve economic advantages. On the contrary, the total cost of intermodal system ascended along with the increase of open UD, while the transport cost dropped due to the advance in network connectivity. Both trends were relatively stable. Therefore, in M-ULS-integrated logistics system, optimal cost is not sensitive to the number of UD opened. It is considerable to set up additional underground depots so that the capacity and robustness system service can be further augmented.

7. Conclusions

This paper developed a multistage model with a combined algorithm based on hierarchical optimization, which aimed to deal with optimal nodes location-allocation problem in the cooperative operation of M-ULS. The applicability of the model was proven by selecting the appropriate metro lines and stations

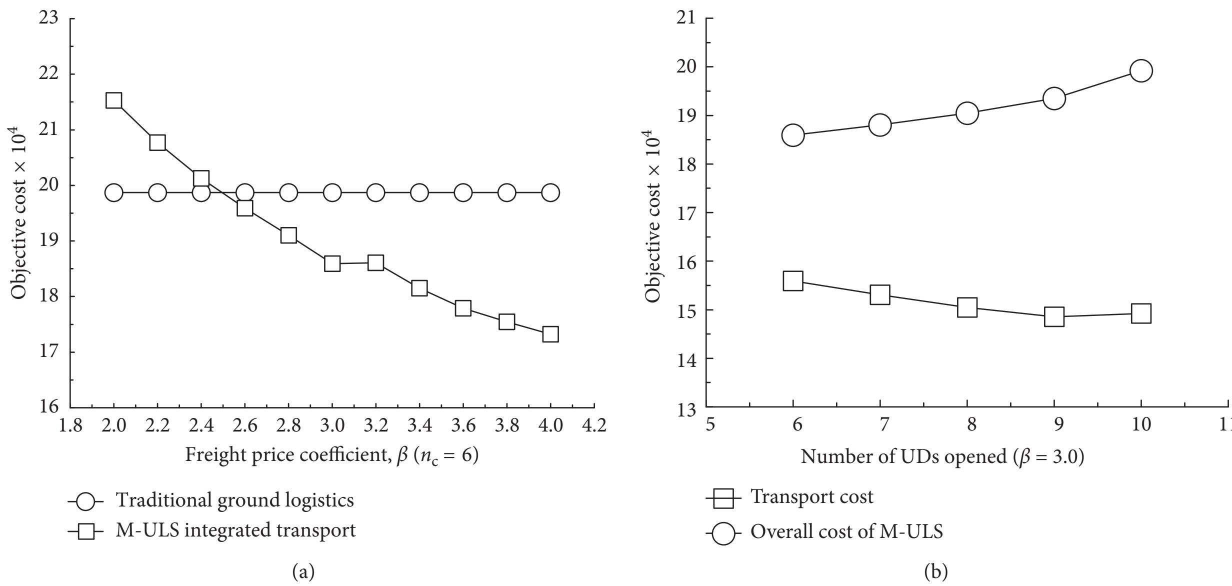

Figure 7: Variation of objective cost against the change of β and n_c.

for problem solving. The critical issue of developing a M-ULS network is to establish an operational framework and optimization method for multiple nodes. Three types of nodes were defined as underground depot (UD), underground hub (UH), and ground terminal (GT), in accordance with the current state and planning of the city, logistics, and metro network. The M-ULS is in limited capacity, which has a multiple network hierarchy and multiple sources of freight. Therefore, it is necessary to screen the demand points and integrate them into the model for global optimization. A set of mixed integer programming model combined with comprehensive evaluation was developed as a more rigorous and convenient analysis approach to solve CM-ULSLAP. The model was embedded with three evaluation variables, namely, UFF, RA, and SD. A hybrid algorithm composed of E-TOPSIS, exact algorithm, and heuristic algorithm was designed to obtain the solution of the model. A real-world simulation based on Nanjing Metro was carried out to verify the effectiveness of proposed models and algorithms.

It was proved that the potential of metro stations and underground tunnels can be fully exploited to achieve higher logistics benefits. According to the results, optimized M-ULS contributed to reducing the overall ground traffic volume by 49.09% and the daily comprehensive cost by 6.44% within the service scope. Served by the new logistics system, 62.47% of the total freight was completed by ULS, and the remaining 37.53% was delivered to all demand points which were delivered by road distribution. Furthermore, compared to traditional point-to-point logistics mode, the price gap of M-ULS optimal cost has mostly remained stable, regardless of the number of UDs. The realization of these advantages neither affects the normal operation of the metro system nor further increases the amount of underground space development. The other comprehensive benefits for urban transport, environment, and society are obvious. This paper not only proposes a well-designed location-allocation model for joint operation of ULS and metro but provides a possible method for the collaborative research of different urban infrastructures. Moreover, it can provide novel ideas for the sustainable urban development.

Despite the above contributions, this study has several noteworthy limitations. First, the proposed model was exclusively applied to cross-shaped or #-shaped radial metro layout. The loop network will have some special problems that cannot be ignored, for example, the trade-off among transshipment efficiency, routing selection, and budget. Second, the proposed deterministic system in which the UHs were always opened was actually not economical. Although the new problem always starts from certainty, future research needs to explore the uncertainty problems. Robust optimization approach can be used to study the UH scheduling strategy under conditions of stochastic disruption and demand uncertainty. Additionally, research on network planning or underground space can be further extended by considering the operational conflicts between M-ULS and metro system.

Data Availability

This study was initiated by the local government. Some data remain protected before the end of the project. The interested reader in this research can send an request e-mail with their consideration to steve_hu@vip.163.com for obtaining the available data. The authors thank for the understanding.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Efficiency Advantages and Incentive Mechanism of PPPs: A Qualitative Comparative Analysis under the Chinese Scenario

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Based on the PPP efficiency system which consists of allocation efficiency, process efficiency, and individual efficiency, we use qualitative comparison analysis of fuzzy sets to study the efficiency advantages of the public-private partnership under the Chinese scenario. The findings are as follows: (1) like public-private partnerships, Chinese-style PPPs have also failed to achieve co-operation. (2) High allocation efficiency can be achieved if competition in bidding processes can be ensured; when bidding procedures cannot be guaranteed to compete, alternatives to high allocation efficiency are either privatized or allocated directly to enterprises that can enable economies of scale; individual effort is a source of allocation efficiency. (3) Competition and economies of scale are necessary conditions for high process efficiency. The private sector's ownership of assets is a sufficient condition for high process efficiency. (4) High individual efficiency can be achieved if individual efforts can be ensured, and high individual efficiency can also be achieved by the competition of bidding procedures or economies of scale when it is impossible to ensure high levels of individual effort. Privatization is the perfect incentive for high individual efficiency when the competition in the bidding process, individual efforts, and economies of scale cannot be guaranteed.

1. Introduction

The government and enterprises (includes state-owned enterprises and private enterprises) cooperation model, which is Chinese-style public-private partnerships, has been rapidly developed and widely used. Public-private partnerships (PPPs) have received increasing attention in China because they are thought to have many benefits [1, 2]. Using PPPs, governments can obtain funds, advanced management, and technologies from enterprises, benefits from cost savings, and on time project delivery [3–5]. Involving the private sector in infrastructure projects will lead to higher quality service delivery, lower administrative costs, will also enable the transfer of risks to private sectors, and "value-for-money" [6–9]. Most of the above advantages of PPPs are efficiency issues, compared to traditional public-sector provision; efficiency and productivity improvement are the fundamentals of PPPs [10]. However, this is not a natural and unquestioned proposition [11–13]. At the same time, private enterprises may obtain no gain from improving efficiency; it is fixed at a specific level by the concession agreement in a PPP project.

The reason for involvement of the private sectors is that they are uniquely determined in the presence of the difference between the efficiency of traditional provision and PPPs approach. The differences are reflected in the theoretical efficiency advantages and the undoubtedly high transaction costs [14]. Given the obvious complexity, PPPs have higher transaction costs than traditional public procurement. According to Allen (2001), bidding costs to all potential contractors have reached as much as 3 percent of expected total project costs, regardless of project size, which is 3 times higher than in traditional provision [15]. Besides, a PPP project has higher monitoring costs, and empirical evidence from the United States shows that monitoring performance of the private sector partner in PPPs projects entails extra costs anywhere between 3 and 25 percent of the contract value [16]. PPPs have higher transaction costs, which needs no further discussion.

In contrast, applicability of PPPs depends on whether it can realize potential efficiency advantages or not. Especially in the context of China, state-owned enterprises have also been seen as the private sector; therefore, Chinese-style public-private partnerships has distinct internal configuration, and the efficiency advantages of Chinese-style PPPs will be different. Meanwhile, efficiency advantages and incentive issues are two sides of a coin for the application of PPPs. Efficiency is a question of economics, while motivation is about management. It means that we can improve the efficiency of PPPs projects by stimulating private sectors; it also means that we can explore and unearth more other sources of advantages by using incentive mechanisms. The research question for this study is, "Compared to traditional procurement, what kind of efficiency advantages does Chinese-style PPPs have? And what are the incentives that are consistent with these efficiency advantages?"

This article is structured as follows: Section 2 describes efficiency of PPPs projects, its implications for the research approach, and the applied research approach of fuzzy-set Qualitative Comparative Analysis (fsQCA). Section 3 sets the empirical scene by introducing the process of survey and the data collection. Section 4 analyzes data using the fsQCA method. Sections 5 and 6 comprise the discussion and conclusions, respectively.

2. Efficiency of PPP Projects

2.1. Efficiency System of PPPs Project. Partners from different sectors in PPPs may bring distinctive advantages to collaborative endeavor [17, 18]. Public-sector partners hold particular mandates or powers [19], which enable them to target at special issues, such as situations of market failure; private sector partners may possess the ability to maximize value for money and thus deliver outcomes at lower cost [20, 21]. In PPPs, the public-sector safeguards allocative efficiency and the private sector ensure productive efficiency [10]. Free competition market without public-sector intervention provides the most efficient way to allocate scarce economic resources to competing uses. Therefore, under the hypothesis of efficient market, allocative efficiency and production efficiency cannot be divided into two branches that are separately responsible for different subjects. For infrastructure and public services, this distinction provides an excellent research perspective.

However, the distinction between allocation efficiency and production efficiency benefits economic explanations but does not contribute to project management. To compensate for this defect, following the above logic, we elaborate the rule that different subjects dominate different types of efficiency. First of all, the atomic decision-making units are the individuals rather than the public or private organizations [22]. The efficiency associated with it is clearly different from the allocation efficiency, because initially we were not sure what the source of this particular efficiency was, and Leibenstein called it X-efficiency [23]. However, this efficiency is ultimately reflected in the autonomy of the individual, in the PPP project scenario, called the individual efficiency. Specific issues of the project also depend on the individual efforts; therefore, individual efficiency can be seen as an important part of production efficiency. Secondly, PPPs can be defined as cooperation between public and private actors with a durable character in which actors develop mutual products and services, and meanwhile, risk, costs, and benefits are shared [24]. Cooperation reflects the fundamental value of PPPs, and separation of allocation efficiency and production efficiency reflects the division of labor, but it does not reflect cooperation. Process efficiency concept came into being, which emphasizes the efficiency of the project implementation process. Only effective cooperation can achieve process efficiency, and process efficiency is also an important part of production efficiency. According to different efficiency subjects, this paper expands the efficiency of PPP projects into a system that includes allocation efficiency, process efficiency, and individual efficiency. Table 1 provides an overview of efficiency types and its subjects.

Table 1: Efficiency types and their subjects.

Efficiency	Subjects	Stage of project
Allocation efficiency	Public sector	Bidding stage
Process efficiency	Public and private sectors	Project life cycle
Individual efficiency	Private sector	Project life cycle

The three efficiencies in this efficiency system have different theoretical foundations. Among them, allocation efficiency is based on the theory of Pareto efficiency, individual efficiency is derived from X-efficiency theory, and process efficiency is based on the cooperative concept advocated by the PPP model. Identifying efficiency subjects helps clarify the responsibilities of many participants in the PPP project. In a perfect competitive market or a pure public goods market, it is completely unnecessary to distinguish efficiency subjects. As a value-staggering approach, the PPPs need to take into account the attributes of the public sector and the private sector. Taken together, the unique PPP projects originate from the hybrid attributes of private goods and public goods, which is the theoretical basis of the efficiency system proposed in this paper.

2.2. Sources of Efficiency Advantage and Incentives. When it comes to the term efficiency advantage, it implies a comparison to the traditional provision. In typical PPPs, private sector organizations operate in an economic environment of contestable resource markets. Pressure to maximize the value of shareholders together with the threat of mergers and acquisitions should ensure that the value is maximized from resources controlled by the private sector [25, 26]. With fewer formal decision-making procedures and less administrative oversight, the private sector can be less hampered by bureaucratic rules and controls [27]. Therefore, the earlier research was based on the comparison between government attributes and market attributes, and it was believed that PPPs have efficiency advantages. Besides, Hart took an incomplete contract as a research perspective, and believed that the choice between PPPs and conventional provision was made on whether it is easier to write contracts on service provision than on building provision; PPP is efficient if the quality of the service can be well specified in the initial contract [28].

Later studies have paid more and more attention to the project itself, which is the issue of economic characteristics of PPPs. Theorists attribute the private sector's efficiency advantages to three distinct mechanisms, which are contestability effect, ownership effect, and scale effect [29–34]. PPP is a procurement model in which the value for money is optimized through efficient allocation of risks, whole life service approach, private sector management skills as well as synergies from interlinking the design, finance, construction, and operations [35]. It can be summarized as a competitive tendering process [29], the binding of different project links [36, 37], private ownership of project assets in a specific period, economies of scale, risk transfer [38–40], and cooperation [24, 41]. In accordance with the viewpoint of Klijn and Teisman, due to the different core business between the public and private sectors, different values and strategies, joint decision-making is impossible, and cooperation is difficult to achieve [24]. At the same time, ownership and binding are not suitable for separation processing; only when ownership is clear, binding can be realized, and only when binding is realized, ownership is meaningful. In addition, according to X-efficiency theory, PPPs may change the inert area [23] of the individual compared to the traditional provision methods, which means the improvement of individual efforts. And the individual effort may also come into the potential source of efficiency advantage of PPPs, and empirical studies support this view [42].

2.3. Configuration Ideas and QCA. The efficiency advantages of typical PPPs may not be established in Chinese-style PPPs, and the efficiency advantages that are not established in typical PPPs may be realized under Chinese-style PPPs. In order to clarify the source of efficiency advantages of Chinese-style PPP, we conduct empirical research that includes all potential advantages. The empirical research is operated under the above efficiency system that consists of allocative efficiency, process efficiency, and individual efficiency. Efficiency is more likely to result from a combination of multiple efficiency advantages than a single efficiency advantage. Therefore, this issue is related to complex cause and effect rather than simple one. Ragin believes that these issues are suitable for configuration analysis [43]. Qualitative comparative analysis (QCA) is a method of configuration analysis, which is a case-based comparative method. The core idea of QCA is the idea of configuration; it considers research objects as an inseparable organism. In mainstream applications, cases are the main research objects. However, the QCA method is not limited to case studies as long as it does not violate the concept that the object of analysis is an inseparable organism. This article treats each investigated individual as an indivisible research object, and this approach fully complies with the application logic of the QCA method. In other words, all the information provided by participants on PPPs is whole. The study strategy of discarding information fragmentation is abandoned.

Following the properties explained above, the research approach used for the present study consists of several steps [44]. The first step is about the grounded collection of data, which was conducted through a structured questionnaire. This allowed the researcher to obtain the participant's view, attitude, experience, and intuitive feeling about the PPP project which they take part. In the second step, the questionnaire information was qualitatively coded. Qualitative coding is a process where codes are developed and can be revisited as the researcher interprets the data [45]. The third step is the application of the QCA method, which is an umbrella term for several subtypes, including fsQCA [46]. Being case-based, it allows researchers to emphasize the unique aspects of cases, while still allowing the identification of patterns among them through comparison [45]. In QCA, the aspects of cases are named "conditions."

QCA analysis can also be divided into several subroutines. The first subroutine is the grounded cases as configurations, based on the coded structured questionnaire. The configurations are placed in a data matrix after coding cases quantitatively, and the cases are put in the rows and the conditions in the columns in the matrix. The second subroutine is to convert the data into so-called truth table, which sorts the cases over the logically possible configurations that are present in the data [47]. Each row in the truth table, which is a fundamental tool for the comparative analysis, can be read as a statement about whether the configuration represented in the row is "true" for the corresponding outcome. The third subroutine involves the pairwise comparison of configurations that have the same outcome but differ in one other condition, that is, the truth table minimization process. The last subroutine is to interpret the patterns that result from the truth table minimization so as to understand the efficiency advantage sources of corresponding type efficiency in this study.

3. Data Collection

3.1. Research Background Information. This article examines the sources of efficiency advantages of the PPP approach under the Chinese scenario. In other words, PPP is seen as a relatively abstract concept, rather than a specific project or a category of projects. Therefore, practitioners and researchers who have a personal experience of Chinese-style PPPs are the most objective, and their attitudes and opinions can best reflect China's reality. According to the logic of the QCA method, this article regards everyone's evaluation and views on related issues as an integral organism. In case study terminology, this article treats the view of each participant or researcher involved as a case.

The data needed for the study was obtained through a structured questionnaire. The study population was focused on PPP researchers in universities and research institutes and PPP practitioners in the government sector, private sector, consulting agencies, and financial institutions. The survey lasted for more than six months; 236 questionnaires were distributed and 211 were recovered, of which 174 were valid questionnaires. Because the QCA method is applicable to small-scale, medium-scale, and large-scale samples, the sample size can still be adjusted during the analysis process. At the same time, 174 valid samples are strictly screened through the time of answering questions, the number of years of employment, and reverse items. With the help of second-hand data such as specific project information and literature data, the

Table 2: Sample background information.

Types	Classification	Sample scale	Percentage
Subject attributes	Public sector	16	19.5
	Private sector	20	24.4
	Consulting agencies	12	14.6
	Research institutes	26	31.7
	Financial institutions	8	9.8
Years of service	Less than 1 year	3	3.7
	1 to 3 years	29	35.4
	4 to 6 years	9	11.0
	7 to 9 years	7	8.5
	10 years and above	34	41.5
Subject's type of project	Transportation project	33	40.2
	Municipal related	36	43.9
	Agriculture and environment related	11	13.4
	Comprehensive development related	19	23.2
	Social utilities and others	33	40.2

questionnaire was further reviewed and 82 samples were finally retained as analysis data. The corresponding background information of the structured questionnaire is shown in Table 2.

The background data from the subjects were found as follows: (1) the number of participants from governments, private sectors, and consulting agencies was 16, 20, and 12, which corresponded to 19.5%, 24.4%, and 14.6%, respectively. These three types of subjects were the most direct practitioners of the PPP program, and these proportions are relatively balanced. The highest proportion of subjects is the PPP researcher of scientific research institutions, which is 31.7%. Its proportion is not dominant, and researchers receive comprehensive information from public sectors, private sectors, consulting agencies, financial institutions, and academics frontier. Researchers' attitudes are more neutral and objective than practitioners in other sectors and do not have a negative impact on research validity. (2) Judging from the types of participants involved in the project, the proportion of the five categories is relatively balanced, with the lowest share of the agriculture, forestry, and water conservancy projects being 13.4%, which is related to the relatively small percentage of such projects. The above data are basically consistent with the project data released by the Ministry of Finance and the National Development and Reform Commission. (3) From the perspective of the practitioner's employment time, 61.0% of the employees had worked for more than 4 years. Another 35.4% of the participants had a working time of 1 to 3 years. This period is in line with the time the government has pushed PPPs. Therefore, 61.0% of the subjects have relatively rich project experience, and more than 96% of the subjects have a deeper understanding of PPPs, which means that the reliability of the survey data can be ensured.

3.2. Variables of Conditions and Outcomes. According to the previous argument, there are six variables in the preexisting conditions: competition, ownership and binding, risk transfer, economies of scale, cooperation, and individual efforts. Allocation efficiency, process efficiency, and individual efficiency are the outcome variables. In the structural questionnaire, each variable corresponds to some measurement items. Theoretically, there are two methods to determine the weight of each item. One option is to use the confirmatory factor analysis (CFA) to determine the factor load of each item and then use the factor load as the basis for calculating the weights, and another option is to determine weights by means of expert scoring. The former is based on statistical logic of random sampling, and the latter is based on subjective experience evaluation. Considering that the QCA method itself has a logical basis completely different from the mainstream statistical methods, and in order to better reflect the qualitative comparative characteristics of the QCA, the expert rating method is used in this paper to determine the weights. The corresponding condition variables and result variables are described in Table 3.

3.3. Data Calibration. Calibration is the process of data adjustment, so that by the calibration, results will have interpretability. The use of fuzzy-set calibration is based on some certain criteria to adjust the scores of the conditions and outcomes to the explainable affiliation, and the degree of membership is between 0 and 1, where 0 means completely nonaffiliated and 1 means completely subordinated. In the calibration procedure of the operating software fsQCA 2.0, it is necessary to set three thresholds that are completely unaffiliated, fully affiliated, and crossover points [43]. The three points in this article are set to 5, 4, and 1, respectively, that is, a weighted average score of 5 means "completely subordinated", 1 means "completely unaffiliated", and an intersection 4 means "not totally subordinate or not completely nonaffiliated." The purpose of setting a higher intersection is to obtain more robust analysis results, as shown in Table 4:

4. Analysis

4.1. Necessity of Single Preconditions. For qualitative comparative analysis, causality is constructed through sufficient conditions and necessary conditions. If a condition always occurs when a result is produced, this condition is a necessary condition for the corresponding result; if a result is always produced when a condition occurs, then the condition is

Table 3: Brief description of variables.

Variables		Brief description
Outcomes	Allocation efficiency (EALL)	The project can apply PPP. The project is a public need. The government selected qualified private sectors for the project.
	Process efficiency (EPRO)	There is no dispute about the distribution of risks and benefits, and there are dispute resolution clauses in the contract. The private sector expertise is presented in the project, and the government's experience in the public project area is reflected in the project.
	Individual efficiency (EIND)	Employees have professional knowledge and skills; they invest their energy and wisdom and need to work overtime.
Conditions	Competition (COM)	The private sector is actively participating in bids and is enthusiastic about its strength. The successful bidder has an advantage in financing capacity, construction capacity, or operating ability.
	Ownership and bundling (OWN)	The private sector has ownership and is free to make decisions. When operating the project, they simultaneously take into account all aspects of the project.
	Risk transferring (RIS)	The public and private sectors are good at managing the risks assigned to them
	Economies of scale (SCA)	The successful bidder has similar project experience and will also participate in bidding for other similar projects.
	Cooperation (COO)	The public and private sectors can compromise on differences of opinions and differences of interests, and they will have mutual trust and equal status.
	Individual efforts (IND)	Practitioners feel the competition, also felt the opportunity to have a good career, and satisfactory remuneration.

Table 4: Calibration guidelines.

Variables		Target set	Anchor points
Outcomes	Allocation efficiency (EALL)	High allocative efficiency	5 means completely subordinated; 1 means completely unaffiliated; and an intersection 4 means the crossover points
	Process efficiency (EPRO)	High process efficiency	
	Individual efficiency (EIND)	High individual efficiency	
Conditions	Competition (COM)	Perfect competition	
	Ownership and bundling (OWN)	Property rights are clear and ideally bundled	
	Risk transferring (RIS)	Reasonable risk transfer	
	Economies of scale (SCA)	With economies of scale	
	Cooperation (COO)	Effective cooperation	
	Individual efforts (IND)	High-level individual effort	

a sufficient condition for the corresponding result. The necessary condition is an indispensable condition that leads to the occurrence of the result, but it does not mean that the result will inevitably occur. Based on the assumptions of multiple concurrent causalities, the necessary and sufficient conditions in social sciences do not exist. The QCA analysis seeks causality by establishing a combination of sufficient conditions. Therefore, it is necessary to determine whether the conditions of each antecedent condition variable are the necessary conditions for the outcome variable. If it is a necessary condition, it may not be considered when searching for a sufficient conditional combination later. The condition variable is a necessary condition for the corresponding result, when the current consistency between the condition variable and the result variable reaches 0.9 [48]. Necessity of calculation software derived from single condition is shown in Table 5. According to the standard of consistency 0.9, competition is a necessary condition for process efficiency. Weak cooperation or noncooperation is a necessary condition for high allocation efficiency, high process efficiency, and high individual efficiency. This means that in the current stage of Chinese-style PPPs, the degree of collaborative cooperation is still low. Cooperation has not become a source of Chinese-style PPP's efficiency advantage. It is difficult to achieve effective cooperation under the Chinese scenario, like the Western developed countries.

Table 5: The necessity of single preconditions.

Conditions		Outcomes Necessity Allocation efficiency EALL	Process efficiency EPRO	Individual efficiency EIND
Competition	COM	0.85	0.93	0.79
	~COM	0.81	0.82	0.78
Ownership and bundling	OWN	0.62	0.76	0.59
	~OWN	0.93	0.92	0.89
Risk transferring	RIS	0.81	0.88	0.79
	~RIS	0.83	0.84	0.78
Economies of scale	SCA	0.87	0.90	0.84
	~SCA	0.77	0.80	0.73
Cooperation	COO	0.51	0.62	0.47
	~COO	0.95	0.98	0.95
Individual efforts	IND	0.80	0.86	0.77
	~IND	0.81	0.85	0.79

Note: preceding a variable, the symbol "~" represents the logical operator "NOT."

Table 6: The configuration of allocation efficiency.

Conditions	Configuration EALL1	EALL2	EALL3	EALL4	EALL5	EALL6	EALL7
COM	⨂		●	⨂	⨂	●	●
OWN	⨂	⨂	⨂	●	●	●	●
RIS		⊗	⊗	⊗	•	•	•
SCA	⨂	●		⨂	●	●	●
IND	●	⨂	⨂	⨂	⨂	⨂	●
Consistency	0.89	0.85	0.87	0.92	0.95	0.94	0.91
Coverage	0.62	0.69	0.67	0.45	0.50	0.46	0.64
Overall solution consistency				0.80			
Overall solution coverage				0.87			

Note: ●• indicates that the corresponding conditions exist. ⨂⊗ means the corresponding conditions do not exist. ●⨂ refers to the core condition. •⊗ refers to the auxiliary conditions. No marking means that the corresponding condition does not matter.

4.2. High Efficiency Configuration. In the efficiency configuration analysis, the consistency threshold was set to 0.80 and the sample threshold was set to 1. According to this standard, the sample sizes in the allocation efficiency configuration, process efficiency configuration, and individual efficiency configuration were 25, 40, and 25, respectively. Analysis software usually gives complex solutions, simple solutions, and intermediate solutions for qualitative comparative analysis. The intermediate solution is the main basis for the QCA method, because it can avoid the cumbersome nature of the complex solution and the irrational nature of simple solution. From the analysis above of the necessary conditions, it can be inferred that weak cooperation is a necessary condition for all three types of efficiency. In addition, competition and economies of scale are also necessary conditions for process efficiency. Therefore, in the analysis of sufficient conditions, which is the analysis of the efficiency configuration, the effects of cooperation variables are ignored. When analyzing the process efficiency configuration, the impact of competition variables and economies of scale should be ignored, which is for the reason that they must exist in the corresponding efficiency configuration and do not require redundant analysis. High allocative efficiency configuration arranged is shown in Table 6.

Consistency and coverage are an important basis to evaluate the relationship between conditional configuration and outcomes. It can be seen from Table 6 that the consistency of all 7 conditional configurations is greater than the theoretical value of 0.8, which means that the samples of these 7 conditional configurations all meet the consistency requirements. These 7 configurations are all sufficient conditions for the high allocation efficiency of PPP projects. The overall consistency index is also greater than 0.8, further indicating that the resulting conditional configuration is a sufficient condition for high allocation efficiency. Coverage measures the extent to which the conditional configuration interprets the result. The greater the coverage is, the greater the interpretation of the result by the corresponding configuration will be.

The process efficiency configuration is shown in Table 7. There is only a sufficient condition for process efficiency configuration. It consists of three variables, of which ownership and bundling are core conditions, individual effort is an auxiliary condition, and risk transfer is not important to the configuration. Configuration consistency of 0.86, more than the theoretical value 0.8, the resulting configuration is indeed the sufficient condition for high

Table 7: The configuration of process efficiency.

Conditions	Configuration EPRO1
OWN	●
RIS	
IND	⊗
Consistency	0.86
Coverage	0.71
Overall solution consistency	0.86
Overall solution coverage	0.71

Note: ●● indicates that the corresponding conditions exist. ⊗⊗ means the corresponding conditions do not exist. ●⊗ refers to the core condition. ●⊗ refers to the auxiliary conditions. No marking means that the corresponding condition does not matter.

efficiency of the process, and the configuration of coverage of 0.71. Considering that process efficiency emphasizes the project implementation process and cooperation process, which is, the effectiveness of integrating different links of projects, it depends more on management technology than on individual efforts. The private sector tends to use advanced management techniques when they have the project asset ownership.

Without the involvement of the variable of cooperation, the analysis of individual efficiencies finally yielded seven high-efficiency conditional configurations consisting of the other five conditions, as shown in Table 8. In these configurations, competition, ownership and bundling, economies of scale and individual efforts are the core conditions, and risk transfer is an auxiliary condition. The consistency of the configurations is greater than the theoretical value of 0.8, which is a sufficient condition for high individual efficiency. The overall solution consistency was 0.86, which also exceeded the theoretical value of 0.8. The overall solution coverage was 0.84, which represents the degree of interpretation of configurations.

Individual efficiency and allocation efficiency have a high degree of similarity only from the perspective of the configuration, the reason for which is that high allocation efficiency results from a competitive tendering process; the private sector will translate this competitive pressure into higher individual efforts, ultimately reflected in the higher individual efficiency. Therefore, the internal mechanism is completely different regardless of the similar configuration. In the discussion section of the paper, there will be more detailed derivation on the above three efficiency configurations.

5. Discussion

5.1. Discussion of the Results. The configuration above is an evaluation of the current Chinese-style PPP by practitioners and researchers, reflecting their attitudes and opinions. In the PPP project efficiency system which consists of allocation efficiency, process efficiency and individual efficiency, weak cooperation is a necessary condition for project efficiency. This article does not support the opinion that cooperation is a source of Chinese-style PPP's efficiency advantages. In public-private partnerships, the reason why cooperation is difficult to be achieved lies in the huge differences in the core business, values, and strategies between the public and private sectors. But under the Chinese scenario, we speculate that it has completely different causes. In China's PPP practice, state-owned enterprises dominate the private sector. There are no irreconcilable differences between the public and private sectors in values, strategies, and interests. The public sector and state-owned enterprises are more closely related to administrative affiliation than to equal cooperation. Based on the reality mentioned above, the public sector is accustomed to its strong position and the private sector is accustomed to its subordinate status, and cooperation will be difficult to achieve as well. According to discussion above, a proposition on cooperation can be drawn. In the following part, cooperation is no longer discussed.

Proposition 1. *Like public-private partnerships, Chinese-style PPPs are also difficult to achieve true joint decision-making and joint actions. Cooperation is not a source of efficiency advantages for Chinese-style PPPs.*

5.1.1. Configuration of Allocation Efficiency. PPPs are mainly used in infrastructure and public service areas which have strong public good characteristics. These are areas where the private sector leads to supply shortages and efficiency losses. In order to avoid the loss of allocation efficiency, the allocation process is implemented by the government through a competitive bidding process. Obviously, competition is the core condition for configuration efficiency, and all the configurations of high allocation efficiency are further classified and merged according to whether competition conditions exist or not. When competition conditions exist, that is, under the condition that the competitiveness of the tendering stage can be guaranteed, the configuration 3, configuration 6, and configuration 7 are obtained. The combination of these three configurations found that, as long as the competition in the tendering stage is ensured, a higher allocation efficiency can be achieved regardless of the existence of other conditions such as individual effort, scale economy, and risk transfer. If competition conditions do not exist, that is, when it is not possible to ensure the competitiveness of the bidding stage, the results are configuration 1, configuration 4, and configuration 5. Configuration 1 emphasizes individual effort, which means that even if other conditions are not met, high configuration efficiency can still be achieved as long as a high level of individual effort is ensured. However, what can only be determined is that individual efforts are the source of allocation efficiency; we cannot recognize the intrinsic link between individual efforts and other conditions. The combination of configuration 4 and configuration 5 emphasizes ownership and binding, which is highly compatible with the privatization or BOO (Build-Operate-Own) model in practice. In other words, even if it is not possible to ensure competitiveness, only if the privatization of related assets can be achieved, a high level of allocation efficiency can be achieved, and the resource allocation process is closer to the market mechanism. If the competition in the tendering stage is irrelevant, without other conditions, it corresponds to the

Table 8: The configuration of individual efficiency.

Conditions	Configuration						
	EIND1	EIND2	EIND3	EIND4	EIND5	EIND6	EIND7
COM	⊗		●	⊗	⊗	●	●
OWN	⊗	⊗	⊗	●	●	●	⊗
RIS		⊗	⊗	⊗	•	•	•
SCA	⊗	●		⊗	●	⊗	●
IND	●	⊗	⊗	⊗	⊗	⊗	●
Consistency	0.93	0.89	0.89	0.96	0.98	0.98	0.97
Coverage	0.59	0.62	0.62	0.43	0.47	0.44	0.62
Overall solution consistency				0.86			
Overall solution coverage				0.84			

Note: ●• indicates that the corresponding conditions exist. ⊗⊗ means the corresponding conditions do not exist. ●⊗ refers to the core condition. •⊗ refers to the auxiliary conditions. No marking means that the corresponding condition does not matter.

situation of configuration 2. Direct allocation of resources to the private sector with economies of scale, from the perspective of allocative efficiency, is equally efficient. Therefore, the following proposition about allocation efficiency is drawn.

Proposition 2. *Competitiveness leads to high allocation efficiency, regardless of the existence of other conditions.*

Proposition 3. *Individual effort is the source of allocative efficiency.*

Proposition 4. *If competition cannot be ensured, but privatization is suitable, then privatization leads to effective allocation.*

Proposition 5. *When competition is irrelevant and not suitable for privatization, risk transfer and individual efforts cannot be guaranteed, and project allocation to the private sector with economies of scale is also effective.*

5.1.2. Configuration of Process Efficiency. Competition and economies of scale are also necessary conditions for high process efficiency, which means high process efficiency can be achieved only if competitive and economies of scale are ensured. Under the above premise, only a sufficient conditional configuration of high process efficiency is obtained, that is, the configuration conditions of ownership and nonindividual efforts result in high process efficiency of PPP projects. The effectiveness of PPP needs to give the private sector sufficient free decision-making space and clear attribution of ownership. Although the emergence of nonindividual conditions has puzzled us, process efficiency focuses on the convergence of different aspects of the project and emphasizes the implementation process of the partnership. As a result, individual efforts that are out of step or even contrary to the project plan may harm process efficiency. The proposition about process efficiency is as follows:

Proposition 6. *Competition, economies of scale, ownership and bundling are sources of process efficiency.*

Proposition 7. *High process efficiency can be achieved only if competitive and economies of scale are ensured.*

5.1.3. Configuration of Individual Efficiency. The theoretical basis of individual efficiency is Leibenstein's X-efficiency theory. Depending on whether it is based on theory or the results of fuzzy-set qualitative comparative analysis, individual efforts are the core conditions of individual efficiency. Therefore, the resulting configuration is classified and merged based on whether individual efforts exist. If the core condition exists, corresponding to configuration 1 and configuration 7, the combination of the two means that the configuration condition of high individual efficiency is individual effort and nonownership. Considering China's practice, the public sector has ownership in many cases, and the private sector cannot decide freely on their own. Nonownership conditions are therefore highly modeled on China's practice, and individual efforts are the key source of individual efficiency.

When the individual effort does not exist, it corresponds to the case of configurations 2, 3, 4, 5, and 6. They are further categorized and merged based on whether ownership conditions are met. Among them, the ones that are more in line with China's practice are the nonownership ones corresponding configuration 2 and configuration 3. Mergers can be achieved, as long as they have economies of scale and competitive characteristics, even if it is difficult to ensure individual efforts, ownership, and risk transfer, and high individual efficiency can still be achieved. It can be inferred that economies of scale and competition have produced effective incentives for individuals. In addition, configuration 4 can be interpreted alone as being suitable for privatization. The private sector is more adept at motivating individuals and making more efforts than the public sector, so other conditions are not important. Configuration 5 and configuration 6 mean that for those projects which do not ensure individual efforts, the private sector has more autonomy, and clears risk transfer, if the bidding process is competitive or the economy of scale is reached, it can also achieve high individual efficiency, which still embodies the incentive effect of competition and economies of scale on individuals. Based on the above derivation, the propositions on individual efficiency are as follows:

Proposition 8. *Individual efforts lead to individual efficiency even if other conditions do not exist.*

Proposition 9. *If individual efforts cannot be ensured, additional incentives are needed to achieve individual efficiency and competition and economies of scale are effective incentives.*

Proposition 10. *Privatization is the perfect incentive for high individual efficiency if the project is suitable for privatization.*

All the discussion and propositions above rarely involve risk transfer. The reason is that in our efficiency system, risk transfer is only an auxiliary condition for the efficiency configuration. After the configuration classification is merged, the condition will be degraded. In practice, the basic principles and implementation rules for risk allocation and risk transfer are relatively clear and can be widely accepted, and risk transfer problems can be better resolved.

5.2. Efficiency Advantage and Incentive. From the perspective of overall project efficiency, competition, individual effort, ownership and bundling, economies of scale, and risk transfer are sources of PPP's efficiency advantage. It is because these mechanisms motivate participants by way of efficient implementation of the project. Each efficiency advantage can be seen as an incentive mechanism, in a sense, PPPs are an organic combination of multiple incentive mechanisms. Especially for individual efficiency configurations, the derivation to the final settlement is always an incentive for individuals. At the same time, we also noticed that all efficiency advantages are related to the private sector, and the corresponding incentives are also incentives for the private sector.

The enlightenment from the above discussion is that if we cluster the clear efficiency advantage into a more abstract incentive mechanism, we can in turn explore more potential efficiency advantages based on the incentive mechanism. The three incentive mechanisms of competitive incentives, intrinsic motivations, and extrinsic motivations can describe all the above efficiency advantages. According to Ryan and Deci, since the material or nonmaterial incentives are all externally controlled, they indirectly satisfy people's psychological or physiological needs, which are called extrinsic motivations [49]. Interests related to the project implementation process itself and feelings of satisfaction and achievement after solving difficult problems will also urge practitioners to move forward, saying it was an intrinsic motivation. The competition itself belongs to extrinsic motivations, considering that the competition of PPP mainly manifests itself as a competitive bidding process, and in view of the importance of competition to the three types of efficiencies in this paper, the competitive incentive is promoted to the same position as the other two.

Among the efficiency advantages identified in this paper, competition is simultaneously affiliated with competition incentives and extrinsic motivations, individual efforts are affiliated with competition incentives, extrinsic motivations, and intrinsic motivations, and ownership and binding are affiliated with extrinsic motivations and intrinsic motivation, economies of scale and risk transfer are extrinsic motivations. Mainstream economics always emphasize extrinsic motivations more. However, it is difficult to achieve effective cooperation under external incentives. For infrastructure projects and public service projects, high efficiency also requires internal incentives. For greater efficiency, we need to explore and apply efficiency advantages derived from internal incentives.

6. Conclusion

This article examines the sources of efficiency advantages of Chinese-style PPP. The efficiency of PPPs is expanded to a system that includes allocation efficiency, process efficiency, and individual efficiency. Based on the configuration idea and fuzzy-set of qualitative comparative analysis method, each efficiency configuration is studied. The study found that (1) competition, individual effort, ownership and bundling, and economies of scale are sources of high allocation efficiency, (2) competition, ownership and bundling, and economies of scale are sources of process efficiency, (3) individual efforts, competition, economies of scale, and ownership and bundling are sources of individual efficiency, (4) risk transfer is not an important source of efficiency advantage for Chinese-style PPP, and (5) like typical PPPs, Chinese-style PPP is also difficult to achieve effective cooperation. The three incentive mechanisms of competitive incentives, intrinsic motivations, and extrinsic motivations can describe all the above efficiency advantages. Its practical value lies in that we can not only use the already-existing efficiency advantages but also excavate more potential efficiency advantages based on incentive regulations.

As a compromise supply way of infrastructure and public service, the attractiveness of PPPs lies in the fact that it can theoretically absorb the advantages of traditional approach and purely private approach while avoiding their own shortcomings. But can it be ensured that the exact opposite would not occur? This article answers the question from the perspective of efficiency advantages and incentive mechanisms. Under the premise of following incentive regulations, as long as the existing and potential efficiency advantages can be fully exploited, PPPs have great potential.

Data Availability

The data used to support the findings of this study are included within the supplementary information file.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Identification of Risk Factors Affecting PPP Waste-to-Energy Incineration Projects in China: A Multiple Case Study

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Waste-to-energy (WTE) incineration technologies are considered an effective solution for sustainable and efficient municipal solid waste (MSW) disposal in China, and the public-private partnership (PPP) arrangement has been widely used to construct and operate WTE incineration projects. However, PPP WTE incineration projects in China are affected by numerous risks due to the long concession period, various participants, and other factors commonly involved in PPPs, resulting in a number of failures. In light of the pivotal role that risk identification, analysis, and response play in the successful development of PPP WTE incineration projects, this paper presents a multiple case study to identify the risk factors involved in China by drawing on experience from the real-life risk events of 35 PPP WTE incineration plants. 18 risk factors are identified; the most critical of which being public opposition risk, environmental pollution risk, government decision-making risk, a defective legal and regulatory system, and MSW supply risk. The results of the study provide a solid foundation for the future risk analysis, risk allocation, and risk response of PPP WTE incineration projects, and shed light on performance improvement of the PPP WTE incineration projects as well as the development of the PPP WTE industry in China.

1. Introduction

The amount of municipal solid waste (MSW) is constantly increasing in China because of its rapid development of urbanisation and industrialisation in the past three decades and continuous improvement of resident living standards. The annual amount of MSW generated reached 203.6 million tonnes in 2016 [1] and is expected to expand to 220 million tonnes by 2020 [2]. The sharply increased in MSW generation over the years puts pressure on such existing MSW disposal methods such as landfill and compost and resulted in a dilemma of "garbage siege" [3].

Incineration is considered the best way to treat the MSW due to low resource consumption, obvious physical volume reduction, less secondary pollution, and energy-recovery [4–6]. Consequently, waste-to-energy (WTE) technology has developed rapidly to provide an effective solution for government to alleviate the pressure of MSW disposal in past decades. WTE incineration in China has developed rapidly since 1988, when Shenzhen built the first WTE plant. According to statistics from the National Bureau of Statistics of China, incinerated MSW increased from 3.70 million tonnes in 2003 to 73.79 million tonnes in 2016, with the number of incineration plants increasing from 47 to 249 over the same period [1, 7].

Meanwhile, subject to budget constraints, lack of management capacity, and other factors, it is difficult for the government to construct and operate high-investment, long-term WTE incineration projects alone. To address the increasing need for WTE facilities, the public-private partnership (PPP) arrangement has been widely used to construct and operate WTE incineration projects, taking advantage of the innovation, know-how, flexibility, and financing provided by the private sector [8, 9]. In China, more than 70% of WTE incineration projects are now operated and supervised by PPPs, and 108 PPP WTE incineration projects with a total investment of CNY 489 billion were deployed from 2012 to 2016 [8, 10].

However, due to the long concession period, involvement of various participants, external uncertainties, and other reasons, PPPs in the WTE incineration industry face more risks than traditional public projects [11–13], which affect their performance and hinder the application of WTE incineration technologies in the MSW disposal industry. In fact, ineffective risk management in the PPP WTE industry has resulted in failure of many incineration projects to reach their expected performance [14, 15]. According to risk management theory, risk identification is the basis of risk analysis and response and is crucial to the performance of risk management [16, 17]. It is therefore essential for both government and WTE private sector investors to have a clear understanding on the risks involved in PPP WTE incineration projects and to establish suitable responsive strategies accordingly.

Nevertheless, although there is ample literature concerning PPP risk identification and analysis, very little is related to the identifications of risk factors affecting PPP WTE incineration projects. Most PPP studies have been conducted to identify risk factors in such other industries as transportation [18], water supply and treatment facilities [19], energy facilities [20], and medical facilities [21]. In addition, the identified critical risk factors of PPP WTE incineration projects vary significantly between countries because of their unique social-economic environments, policies, and regulations [14, 22]. In China, Song et al. [4] and Xu et al. [23] have identified the critical risk factors affecting PPP WTE projects through case studies. However, the cases involved are insufficiently representative to reflect the status of China's PPP WTE industry because their risk events occurred before 2012, when the central and local governments introduced a series of new policies and regulations related to the PPP WTE industry [24].

In response, we conducted a multiple case study to identify the risk factors affecting PPP WTE incineration projects in China over the past decade. The results pave the way for the risk analysis, allocation, and response of PPP WTE incineration projects and are expected to shed light on their performance improvement as well as the development of the PPP WTE industry throughout the country.

2. Research Methods

The research methods used in this study comprise a comprehensive literature review and multiple case studies. The flow of the overall research framework is shown in Figure 1.

2.1. Literature Review. As the most commonly used method of risk identification, risk checklists depend on historical data and experience to list the risk factors of similar projects in a logical order [25]. Accordingly, the literature review provides an auxiliary method of building a risk checklist favoured in many studies [26–29] and is thus conducted here to identify the general risks involved in China PPP WTE incineration projects.

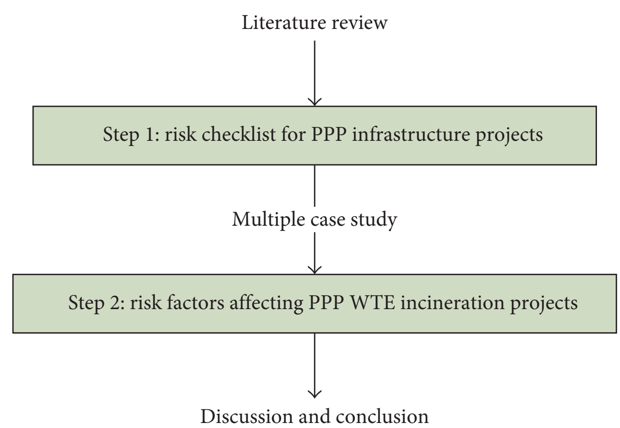

Figure 1: Overall research framework.

The Web of Science was used for the literature research because of its comprehensive coverage of journals worldwide. To address the local literature, the *Journal of Engineering Management* (in Chinese), *Construction Economics* (in Chinese), *Journal of Civil Engineering and Management* (in Chinese) and *Project Management Technology* (in Chinese) were chosen via the China National Knowledge Infrastructure (CNKI) database because they are the most widely recognised construction management Journals in China.

The acronym "PPP," which is used to specifically represent the noun "public-private partnerships," is mentioned in the literature in a variety of forms [2, 30], such as public-private partnerships (PPP), build-operate-transfer (BOT), private finance initiative (PFI), and design-build-finance-operate (DBFO). Therefore, in order to ensure integrity and accuracy, a keyword search process was conducted using the schema of TITLE-ABS-KEY ("public private partnership" OR "build operate transfer" OR "private finance initiative" OR "design build finance operate" OR "PFI" OR "BOT" OR "PPP" OR "DBFO") and TITLE-ABS-KEY ("risk"). From the literature retrieved in this way from selected databases or journals, articles with clear figures, tables, or text descriptions of the identified risk factors were chosen for further content analysis. This involved a total of 54 articles, including 16 Chinese articles and 38 English articles.

The most simple and effective method of identifying risk factors is to establish a risk checklist [31]. This was created in three steps: (1) the risk factors related to PPP infrastructure projects were identified through a comprehensive literature review; (2) these were carefully examined by deleting the inherent risk factors of some categories of PPP projects, for example, the safety risk in PPP highway projects caused by overload and combining risk factors with the same meanings but using different terms; and (3) the risk checklist was established with a clear hierarchical structure through a synthesised risk classification drawn from the literature.

Based on the comprehensive literature review, the risk checklist composed of 54 risk factors was established (Table 1). This follows the classification method of PPP risk factors proposed by Li et al. [26], where the risk factors are divided

Table 1: Risk checklist of PPP projects.

Risk level	Risk categories	Risk factors
Macrolevel risks	1. Political risks	1. Government decision-making risk 2. Government credit risk 3. Government behaviour risk 4. Unstable government 5. Expropriation or nationalisation of assets 6. Strong political opposition/hostility
	2. Legal risks	7. Policy risk 8. Defective legal and regulatory system 9. Industrial regulatory change
	3. Macroeconomic risks	10. Interest rate volatility 11. Inflation risk 12. Foreign exchange risk 13. Influential economic events 14. Poor financial market
	4. Social risks	15. Public opposition risk 16. Market demand risk
	5. Natural risks	17. *Force majeure* risk 18. Weather/geological condition 19. Environmental risk
Mesolevel risks	6. Project selection risks	20. Land acquisition risk 21. Delay in project approvals and permits
	7. Project finance risks	22. High finance costs 23. Project financial attractiveness 24. Availability of finance 25. Inadequate competition for tender
	8. Design risks	26. Design change 27. Design deficiency
	9. Construction risks	28. Construction cost overrun 29. Construction delay 30. Materials/equipment procurement risk 31. Poor-quality workmanship 32. Contract change risk 33. Subcontractors or suppliers risk
	10. Technical risks	34. Technological backwardness 35. Unproven technology
	11. Operational risks	36. Revenue and cost risk 37. Low productivity 38. Insufficient operation capacity 39. Unreasonable concession period 40. Payment risk 41. Residual value risk 42. Lack of supporting infrastructure 43. Frequent maintenance 44. Equipment risk 45. Safety risk 46. Environmental pollution risk
Microlevel risks	12. Relationship risks	47. Organisation and coordination risk 48. Inadequate experience in PPP 49. Inadequate distribution of risks 50. Inadequate distribution of authority 51. Differences in working method 52. Lack of commitment
	13. Third party risks	53. Third party tort and compensation risk 54. Staff crises

into three levels, that is, macrolevel, mesolevel, and microlevel. According to Li et al. [26], macrolevel risks refer to the risks outside the project, mesolevel risks refer to the risks within the project, and microlevel risks refer to the risks of the relationship between stakeholders.

2.2. Multiple Case Studies. The present study aims to identify the "what" and "how" risk factors affecting PPP WTE incineration projects in China. Case studies are appropriate to answer such questions [32]. Meanwhile, PPP WTE incineration projects are still in their infancy in China and

Table 2: Descriptive statistics of the cases.

Profile	Category	Frequency
Location	Eastern China	21 (60%)
	Central China	8 (22.86%)
	Western China	6 (17.14%)
Operation time	Before 2006	10 (28.57%)
	2007–2012	12 (34.29%)
	2013–2017	6 (17.14%)
	Not placed in operation	7 (20%)
Total investment (CNY 100 million)	1–5	25 (71.43%)
	5–10	6 (17.14%)
	≥10	4 (11.43%)
Design capability (tonnes/day)	500–1000	18 (51.43%)
	1000–2000	15 (42.86%)
	2000–3000	2 (5.71%)
Incineration technology	Grate furnace	20 (57.14%)
	Fluidised bed	13 (37.14%)
	Pyrolysis furnace	2 (5.71%)
Current status	Cancelled	5 (14.29%)
	In redecision-making processes	1 (2.86%)
	Under construction	1 (2.86%)
	Placed in operation	26 (74.29%)
	Closed before scheduled closure date	2 (5.71%)

relevant studies are limited. For a new or insufficiently researched field, case studies are the preferred method [33]. Moreover, a single case study is contextually stronger and is not conducive to summarising general rules and promoting the research results [34]. As a result, a variety of case studies are used to provide a range of contexts. The flow of the multiple case studies comprises the following four steps:

(1) *Determining Standards for Case Selection*: in order to fully reflect the current status of China's WTE industry and to ensure the comprehensiveness and representativeness of the cases, the criteria for case selection are as follows: (1) the WTE incineration projects are operated by PPP arrangement, such as BOT and DBFO; (2) risk events significantly that affect their performance occurred during the project lifecycle; and (3) except for some typical and significant cases, the risk events involved occurred after 2012.

(2) *Case Selection and Data Collection*: the systematic analytic process for case selection followed [35]. First, a wide range of sizable samples of actual WTE incineration plants that were heavily affected by the occurrence of a variety of risk events were collected from the literature, research reports, newspapers, and the Internet. Second, a total of 35 cases, which is far more than the usual requirement for multiple case studies [33], were selected as study cases to identify the critical risk factors by using the criteria for case selection determined above. Third, detailed information relating to these selected cases was collected from the Internet, industrial reports, media, academic literature, and other relevant materials, and a desk research of collected data was conducted to prepare materials for the upcoming content analysis. Table 2 provides details of the cases.

(3) *Identifying Risk Factors through Content Analysis*: as an observational research method to evaluate the symbolic content of all forms of materials, either qualitative or quantitative content analysis is frequently used to identify the major facets of a set of data [36]. Thus, content analysis was carried out to identify the risk factors appearing in each of selected cases by utilizing the preferred risk checklist established from the literature review.

(4) *Verifying the Identified Risk Factors by Expert Interview*: interviews with a preestablished team of experts were conducted to verify the appropriateness and comprehensiveness of the identified risk factors. The team consists of three experts with different WTE industry backgrounds—a Hangzhou government-related WTE industry official, a senior manager from a WTE incineration plant (Hangzhou Green Energy Environmental Protection Power Co., Ltd), and a researcher related to WTE implementation.

3. Results

The identified risk factors seriously affecting the performance of each case are summarised in Table 3.

Table 4 summarises the frequency of the risk factors identified in the case studies, divided into high-, medium-, and low-frequency risks. The high-frequency risks (appearing in at least 10 of the 35 cases) comprise public opposition risk, environmental pollution risk, government decision-making risk, defective legal and regulatory system, and MSW supply risk and may heavily affect the performance and development of the WTE incineration industry in China. Medium-frequency risks refer risk factors of the frequency from 4 to 10,

Table 3: PPP WTE incineration cases and risk factors.

Number	Project	Operation time	Risk events	Identified risk factors
1	Ningbo Fenglin WTE incineration project	2001	The supplied MSW could not be burned immediately due to containing a high level of water. Insufficient MSW treatment facilities led to environmental pollution. The residents suggested the government to close the project, which the government promised to do at the beginning of 2014. Finally, the project was closed in June 2014, although there was still a 14-year concession period remaining	(i) MSW supply risk (ii) Environmental pollution risk (iii) Lack of supporting infrastructure (iv) Government credit risk
2	Zhengzhou Xingjin WTE incineration project	2000	Due to insufficient MSW supply, the incinerators had to be used alternately. The operator was suspected of using coal instead of MSW to increase production. The PPP company suffered heavy losses between 2004 and 2005. The transportation cost of MSW was then increased because a new toll station was set up between the CBD and the plant. In 2013, local residents complained that the neighbouring environment was polluted by MSW and wastewater	(i) MSW supply risk (ii) Defective legal and regulatory system (iii) Revenue and cost risk (iv) Government decision-making risk (v) Public opposition risk (vi) Environmental pollution risk
3	Anhui Wuhu WTE incineration project	2003	The on-grid electricity price of waste incineration was so low that the plant suffered heavy losses from 2003 to 2005. The supply of MSW was insufficient from 2003 to 2004	(i) Policy risk (ii) Revenue and cost risk (iii) MSW supply risk
4	Chongqing Tongxing WTE incineration project	2005	Both the quantity and the quality of MSW supplied did not reach the expected standard. There was no municipal sewage pipe network on both sides of the main road, which caused serious environmental pollutions. The owners had signed a new contract beyond the concession contract for their own interests. A safety accident occurred because of the poor design of the transportation vehicles. The MSW disposal fee was not paid on time, increasing the financial pressure of the PPP operator in 2006	(i) MSW supply risk (ii) Lack of supporting infrastructure (iii) Environmental pollution risk (iv) Defective legal and regulatory system (v) Safety risk (vi) Design deficiency (v) Payment risk
5	Kunming Wuhua WTE incineration project	2008	Due to unclear regulations and unsuitable technologies, the private investors from the U.S. decided to withdraw their investment in 2006. The supply of MSW was inadequate so that machines were standing idle. The MSW disposal charge was delayed from 2008 to 2013	(i) Unproven technology (ii) Policy risk (iii) Contract change risk (iv) MSW supply risk (v) Payment risk

Table 3: Continued.

Number	Project	Operation time	Risk events	Identified risk factors
6	Zhongshan Center zutuan WTE incineration project	2006	Both the quantity and the quality of the MSW supplied did not reach the expected standard and some equipment was damaged. In 2006, the incinerators were shut down temporarily to clean up the remains caused by unsuitable MSW, which led to heavy losses. In 2014, due to existing environmental pollution, the plant faced strong opposition from the local community	(i) MSW supply risk (ii) Equipment risk (iii) Environmental pollution risk (iv) Public opposition risk
7	Xuchang Tianjian WTE incineration project	2004	A financial loss emerged in 2008 due to rising coal prices and the low price of electricity generated from the WTE incinerators. The quality of the MSW supplied did not reach the expected standard, and some equipment was damaged. In 2015, 2016, and 2017, the project was fined by local governments for heavy environmental pollution. With rapid urbanisation, increasing numbers of urban residents were living around the originally desolate WTE incineration plant. Due to outdated technologies, it was difficult for the plant to meet China's current emission standards. The plant was finally reconstructed on another site in 2017	(i) Revenue and cost risk (ii) Policy risk (iii) MSW supply risk (iv) Equipment risk (v) Technological backwardness (vi) Environmental pollution risk (vii) Defective legal and regulatory system (viii) Government decision-making risk
8	Beijing Liulitun WTE incineration project	—	The construction site chosen by the local government was located windward of the CBD and close to the water-source protection area of Beijing. The government was trying to conceal risk issues, seriously affecting public credibility. The local residents opposed the project due to potential environmental and health impacts. The project was finally suspended in 2007	(i) Government decision-making risk (ii) Public opposition risk (iii) Government credit risk (iv) Environmental pollution risk
9	Jiangsu Wujiang WTE incineration project	2009	The EIA was insufficient and was considered fake by the local residents. The construction of the project did not stop despite public opposition. Local residents gathered to protest, and the project was finally cancelled in 2009	(i) Government decision-making risk (ii) Public opposition risk
10	Shenzhen Pinghu WTE incineration project	2005	The actual height of the chimney did not match the requirements of the original design documents, resulting in poisonous gas diffusion. The actual situation was not consistent with the promised technical standards, and the equipment for environmental protection did not work for nearly 3 years. In 2009, the local residents opposed the project due to serious environmental pollution involved	(i) Design deficiency (ii) Public opposition risk (iii) Environmental pollution risk (iv) Technological backwardness (v) Equipment risk

Table 3: Continued.

Number	Project	Operation time	Risk events	Identified risk factors
11	Guangzhou Likeng WTE incineration project	2005	In 2010, an explosion occurred in the incinerator causing five people to be injured. The plant was then asked to stop for rectification and reformation. Environmental pollution caused by garbage truck leakage frequently occurred. In 2012, the plant was fined because of the incomplete incineration of MSW	(i) Safety risk (ii) Environmental pollution risk (iii) Defective legal and regulatory system
12	Wuxi Xidong WTE incineration project	2011	The government's publicity for the project was insufficient. In 2011, the residents opposed the plant due to black smoke and a pungent odour. The 90% completed project finally failed and suffered great losses	(i) Public opposition risk (ii) Government decision-making risk (iii) Environmental pollution risk
13	Guangxi Laibin WTE incineration project	2008	The MSW supply was seriously insufficient in 2008. During 2008–2010, production costs increased significantly due to rising coal prices and a defective subsidy mechanism. In 2011, the plant was closed because of maintenance problems	(i) MSW supply risk (ii) Policy risk (iii) Revenue and cost risk
14	Guangdong Huizhou WTE incineration project	2007	Some outdated technologies and second-hand equipment were found to be used in this plant in 2013, resulting in environmental pollution. The project was then opposed by local residents and stopped operation. Some corruption occurred in the bidding process. Relevant monitoring data of the plant were not disclosed in time. The local government finally terminated the contract and started a new one in 2013	(i) Technological backwardness (ii) Equipment risk (iii) Defective legal and regulatory system (iv) Government behaviour risk (v) Public opposition risk (vi) Environmental pollution risk (vii) Contract change risk (viii) Revenue and cost risk
15	Shanghai Jiangqiao WTE incineration project	2003	The EPA did not positively answer the questions raised by hearing representatives. The residents protested over the project's expansion in 2009. In 2013, a major explosion happened because of the lack of on-site safety management and a third party breaking operation rules	(i) Public opposition risk (ii) Government decision-making risk (iii) Safety risk (iv) Defective legal and regulatory system
16	Hanyang Guodingshan WTE incineration project	2012	The plant was constructed in a densely populated area and separated from an existing medical waste incineration plant by a wall. The residents protested due the project's potentially hazardous impact. In 2013, the project was asked to stop for a variety of reasons, that is, starting to operate without authorisation, inadequate environmental protection facilities, and the uncompleted resettlement of the surrounding residents. However, forced by the pressure of garbage siege, the project was reoperated in 2014	(i) Government decision-making risk (ii) Environmental pollution risk (iii) Public opposition risk (iv) Defective legal and regulatory system

Table 3: Continued.

Number	Project	Operation time	Risk events	Identified risk factors
17	Wenzhou Leqing WTE incineration project	2013	The decision-making procedure was questioned by the local residents because most of them were not informed during both the environmental impact assessment process and the planning and construction approval process. To prevent the expansion of the project, several protests were spontaneously organised by the local residents in 2013	(i) Government decision-making risk (ii) Public opposition risk
18	Kunming Donggang WTE incineration project	2012	Half of the machines became idle because of the shortage of MSW supply. The distance between two WTE incineration plants was too close, resulting in a competitive relationship for MSW resources. Payment of the MSW disposal fees was defaulted from 2012 to 2013	(i) MSW supply risk (ii) Equipment risk (iii) Government decision-making risk (iv) Payment risk
19	Hangzhou Jiufeng WTE incineration project	—	The technical-based, traditional top-down decision-making approach has led to strong opposition from the local community. However, the response from local governments was inadequate and insufficient in dispelling the residents' concerns. On May 10, 2014, more than 5,000 local residents protested against the plant, which eventually turned into a mass incident. Finally, the plant was suspended by the local government to restart the decision-making process	(i) Public opposition risk (ii) Government decision-making risk
20	Wuhan north Hankou WTE incineration project	2010	Due to Hankou's rapid urbanisation, the plant was getting closer to the populated residential and commercial areas. The incinerators were not equipped appropriately. In 2014, the local residents protested against the plant because it has caused serious environmental pollution. In the same year, the project was fined by the local government because of illegal disposal of carbon monoxide and fly ash. Finally, the plant was closed and will be rebuilt on another site	(i) Government decision-making risk (ii) Technological backwardness (iii) Public opposition risk (iv) Environmental pollution risk (v) Defective legal and regulatory system
21	Anhui Huainan WTE incineration project	2014	Both the quantity and quality of MSW supplied did not reach the expected standard, and one incinerator was idle due to a shortage of MSW supplies in 2014. Some required equipment such as waste-transfer stations, garbage trucks, and garbage compression equipment was ill equipped. The transportation cost of MSW was too high to be profitable because of the long distance between the CBD and the plant	(i) MSW supply risk (ii) Lack of supporting infrastructure (iii) Revenue and cost risk

Table 3: Continued.

Number	Project	Operation time	Risk events	Identified risk factors
22	Hubei Xianning Fengquan WTE incineration project	2012	The government did not pay the MSW disposal fees on schedule. The operator lacked experience in investing and operating PPP WTE incineration projects. In 2014, the project was ordered to be suspended for rectification because of toxic gas leakage, substandard sulphur dioxide emissions, and so on.	(i) Payment risk (ii) Insufficient operation capacity (iii) Environmental pollution risk (iv) Defective legal and regulatory system
23	Jilin Siping WTE incineration project	2011	Due to the insufficient MSW supplies, a financial loss has emerged since 2012. In 2015, local residents opposed the plant because of the dust, odours, and noise during production. Finally, the plant was forced to suspend production	(i) MSW supply risk (ii) Public opposition risk (iii) Environmental pollution risk (iv) Revenue and cost risk
24	Tianjin Jixian WTE incineration project	2016	There were residents and farmland within 300 m of the plant. In 2016, thousands of local residents jointly signed a petition protesting against the plant for its negative impact on the environment and health of the local community. In addition, the operator of the plant was found to have falsified its environmental impact assessment and health risk assessment. Finally, the project was required to stop in 2016	(i) Government decision-making risk (ii) Public opposition risk (iii) Defective legal and regulatory system (iv) Environmental pollution risk
25	Lanzhou Fengquan WTE incineration project	2016	The local residents were seriously affected by the leakage of odour caused by poor equipment. Some required equipment such as cleaning vehicles was ill equipped. In 2016, some illegal sewage pipes were found to have been built by the operator of the plant, which led to serious environmental pollution	(i) Environmental pollution risk (ii) Equipment risk (iii) Lack of supporting infrastructure (iv) Defective legal and regulatory system
26	Chongqing Wanzhou WTE incineration project	2014	Due to a serious shortage of garbage from 2014 to 2016, insufficient air could be extracted from the upper end of the trash pit to form the negative pressure needed, which led to a serious odour leakage. A line or two lines were run alternately, accelerating equipment aging. The operator lacks experience in investing and operating PPP WTE incineration projects	(i) MSW supply risk (ii) Equipment risk (iii) Environmental pollution risk (iv) Defective legal and regulatory system
27	Haerbing Shuangqi WTE incineration project	2014	The plant was fined by the local government in 2016 for its excessive emission of pollutants, improper disposal of solidified fly ash, and nonstandard operational management	(i) Defective legal and regulatory system (ii) Environmental pollution risk
28	Hubei Xiantao WTE incineration project	—	The technical-based, traditional top-down decision-making approach has led to strong opposition from local communities. In 2016, the project was cancelled by the local government	(i) Public opposition risk (ii) Government decision-making risk

Table 3: Continued.

Number	Project	Operation time	Risk events	Identified risk factors
29	Nanjing Liuhe WTE incineration project	—	As case 28	(i) Public opposition risk (ii) Government decision-making risk
30	Zhejiang Haiyan WTE incineration project	—	As case 28	(i) Public opposition risk (ii) Government decision-making risk
31	Guangdong zhaoqing WTE incineration project	—	As case 28	(i) Public opposition risk (ii) Government decision-making risk
32	Hangzhou Qiaosi WTE incineration project	2002	Due to Hangzhou's rapid urbanisation, the plant was getting closer to the populated residential and commercial areas. The plant was strongly opposed by the local community for its negative impact on the surrounding environment and health. The plant was officially closed in December 2016	(i) Government decision-making risk (ii) Public opposition risk
33	Feicheng Fengquan WTE incineration project	2011	Due to obsolete equipment, constraints on maintenance funds, and other reasons, the pollution control facilities were running poorly and successive excessive pollution problems occurred. The residents constantly complained. In July 2016, the plant operator was interviewed by the local environmental protection department and required to rectify and reform the situation	(i) Equipment risk (ii) Defective legal and regulatory system (iii) Environmental pollution risk (iv) Public opposition risk
34	Shaoxing zhonghuan WTE incineration project	2008	The project was heavily fined in 2016 because the company falsified and illegally deleted automatic monitoring data of discharged exhaust gases and then deleted historical data to circumvent inspection. The residents complained about the pollution involved but did not receive any responses	(i) Defective legal and regulatory system (ii) Public opposition risk (iii) Environmental pollution risk
35	Hainan Wanning WTE incineration project	—	The technical-based, traditional top-down decision-making approach led to strong opposition from the local community. A mass incident has occurred on 12 January 2017	(i) Government decision-making risk (ii) Public opposition risk

while low-frequency risks mean risk factors rarely occurred (no more than 3 times).

4. Discussion

Similar to previous studies identifying risk factors in the WTE incineration industry, the results in Table 4 indicate that numerous risk factors affect the performance the PPP WTE incineration plants and the development of PPP WTE incineration industry in China. On the one hand, although the conclusions of previous studies are not entirely consistent, they provide sufficient evidence that the performance of PPP WTE incineration projects is heavily affected by critical risk factors such as environmental pollution, government decision-making, public opposition, and MSW supply [4, 23]. On the other hand, emerging factors such as safety and government behaviour risks are unexpectedly identified. The reason may be attributed to the fact that low-frequency risks are easily overlooked, especially when those related to local community health and the environment occurred at the same time [37–39]. Moreover, different studies provide different rankings of the importance of the risks. Some argued that the vital factor affecting the development of PPP WTE incineration projects is not technical problems but deficiencies in government regulations and enforcement [40, 41]. Cheung and Chan [42], for example, concluded that government intervention and public credit are severe risks for PPP WTE incineration projects. In contrast with previous studies,

Table 4: Risk factors frequency statistics.

Category	Risk factors	Frequency
High-frequency risks	Public opposition risk	22
	Environmental pollution risk	20
	Government decision-making risk	18
	Defective legal and regulatory system	15
	MSW supply risk	12
Medium-frequency risks	Equipment risk	8
	Revenue and cost risk	7
	Lack of supporting infrastructure	4
	Policy risk	4
	Payment risk	4
	Technological backwardness	4
Low-frequency risks	Safety risk	3
	Government credit risk	2
	Design deficiency	2
	Contract change risk	2
	Unproven technology	1
	Insufficient operation capacity	1
	Government behaviour risk	1

however, our results indicate public opposition risk to be the highest, followed by traditional critical risk factors such as environmental pollution, government decision-making, the defective legal and regulatory system, and MSW supply risks. These are further analysed in the following.

4.1. Public Opposition Risk. The most important reason for public opposition is the emerging “not in my back yard” (NIMBY) syndrome [14], which sometimes manifests in violent behaviour [43]. WTE facilities can be seen as one kind of LULU (locally unwanted land use), of which the benefits are usually broadly distributed, while most of the costs tend to be localised [44, 45]. WTE facilities face considerable and strong opposition from the local communities in which they are situated because they have potential negative impacts (e.g., smell and dioxin release) on local residents’ environments, health, or even property [14, 46]. Protests against incinerators, or anti-incinerator campaigns, have been documented in many countries/regions worldwide [47, 48]. Recently, NIMBYism has become very popular in many potentially hazardous industries in China, especially the WTE industry that, as Table 3 clearly indicates, has led to many WTE projects being cancelled, suspended, or closed before the scheduled closure date. According to public information statistics, at least 10 NIMBY movements related to PPP WTE incineration projects occurred since 2013, for example, the Guangdong Huizhou WTE incineration plant, the Hangzhou Jiufeng WTE incineration plant, and the Nanjing Liuhe WTE incineration plant [49].

Disputes over site selection and decision-making of WTE incineration plants are regarded as the main reason for public opposition [14]. Inadequate disclosure of related information, as well as the inefficient governance and regulation from local governments, are other critical causes by which, once problems occur, it will not only result in a significant loss but also deepen public distrust of the government and PPP WTE incineration projects [49, 50]. Moreover, compensation should also be taken into account [51, 52] for the reason that everyone is highly unlikely to sacrifice their own interests (health and wealth) without adequate compensation [49], with economic compensation considered an effective solution to NIMBY protests [53]. Furthermore, insufficient risk communication between local governments, WTE enterprises, and local communities is also often a significant issue behind public opposition [48, 50].

4.2. Environmental Pollution Risk. Environmental pollution risk occurred in 20 of 35 cases. The collection, delivery, treatment, and incineration of MSW involve complex physical, chemical, and biological processes and can lead to a several forms of environmental pollution [54, 55]. Flue gas from waste incinerators, for instance, contains acid gases, heavy metals, dioxins, and other toxic and hazardous pollutants [23, 24] that cannot be completely eliminated [56]. Waste leachate is another significant source of pollution, and it lacks a mature and reliable treatment technology in China [24]. As happened in Cases 2 and 11, garbage spillage and leakage in MSW collection, delivery, and transportation can also lead to secondary environmental pollution [57]. Consequently, equipment, materials, and technologies for pollution prevention and control need to be used to minimise negative impacts on the environment, which significantly increased WTE operating costs [4, 24]. As one of the most common “negative impacts” of PPP WTE incineration projects, environmental pollution is often caused by the unethical behaviour of practitioners during the construction and operation stage [58], such as through the excessive discharge of contaminating materials and hazardous substance leaks [4], as illustrated in Cases 27 and 33. China’s defective legal and regulatory system, which provided the loophole for private sector’s illegal activities, may be the main contributing reason [58, 59].

4.3. Government Decision-Making Risk. Government decision-making risk is often manifested as inappropriate site selection in the field of WTE incineration, which heavily affects the implementation of WTE incineration technologies in the MSW disposal industry [60], as shown in Cases 8, 16, and 24. As one kind of LULU, site selection and government decision-making related to PPP WTE incineration projects involve not only technical issues but also a complex mix of economic, social, and environmental concerns such as perceived risk and public distrust [61, 62]. Thus, an open and consultative decision-making approach with public participation and transparency is seen as an effective way to ensure the reliability and fairness of the government's decision-making approach [48, 61, 62]. However, although cultivating a strong environmental state remains a key part of China's environmental management strategy, the emerging government decision-making risks indicate that the traditional top-down decision-making approach and the command and control regulation are insufficient to deal with the NIMBY syndrome in the WTE industry [47, 63–66]. In addition, it is worth noting that almost all highly protested WTE projects in China are eventually cancelled or indefinitely postponed by the local governments because the local governments will circumvent unrest through increasing opacity or by selecting sites in locations where public opposition is less likely to emerge [64, 65].

4.4. Defective Legal and Regulatory System. Delivering sustainable PPP WTE incineration projects requires a good supportive legal and regulatory environment [26]. However, the legal and regulatory framework for PPPs, especially for PPP WTE incineration projects in China, is still in its infancy [67, 68]. As a new waste disposal approach, incineration technologies have not been widely used in China's MSW disposal industry until recently, despite the first WTE incineration plant in China being built in Shenzhen in 1988. Thus, many relevant laws and regulations that relate to their establishment and improvement are far less than perfect. For example, the price system of power generation with WTE incineration was basically chaotic until 2012, when the National Development and Reform Committee published a regulation entitled *The Notice on Improving the Price Policies of the Municipal Solid Waste Incineration for Power Generation (2012)* in which the conversion coefficient from MSW to grid-connected power was temporarily determined to be 280 kWh/t and the price of grid-connected power is 0.65 CNY/kWh. This led to the excessive use of traditional energy sources such as coal and diesel fuel in many WTE incineration plants to obtain high benefits from electricity generation. Meanwhile, this risk may also rely on existed legislation and regulations being poorly carried out or even not enforced at all [4, 42], resulting in illegal acts such as excessive pollutant discharge and use of outdated technologies, as shown in Cases 7, 14, 16, and so on. In addition, transparency and open decision-making approaches are essential for establishing a good legal and regulatory framework, or WTE operators may violate the technical and safety standards for their own interests [69]. Finally, frequent changes in legislation are also a major cause of legal and regulatory risks, such as laws relating to land use, tax, labour, and environmental protection [70, 71].

4.5. MSW Supply Risk. In contrast with other risks such as public opposition and environmental risk, the MSW supply risk is a specialised WTE incineration project risk. The inadequate quantity and/or quality of MSW supply are two aspects of MSW supply risk [4]. An inadequate MSW supply will affect the efficiency of PPP WTE incineration projects, both economically and technically. On the one hand, the inadequate supply of MSW caused machines to be idle or to be used interchangeably, which can lead to financial loss and reduced revenues because both disposal fees and electricity fees depend on the amount of waste disposal [23]. On the other hand, a serious shortage of MSW supply may cause incomplete MSW incineration, which leads to incineration gas leakage. In terms of quality, MSW with high moisture content and low calorific value cannot be burned directly [59, 72]. If the MSW is of poor quality, the incineration of waste will require auxiliary fuels, such as coal and diesel, which will not only increase operating costs but also lead to equipment damage [23, 73].

Moreover, compared with similar studies by Song et al. [4] and Xu et al. [23] in China, the current study contributes to the identification of PPP WTE incineration project risk factors by a more comprehensive set of cases as shown in Table 5. The comparative analysis between the three studies shown in Table 5 reveals that the identified risk factors changed with improvements in China's political, economical, and social conditions. Consistent with the findings of Song et al. [4] and Xu et al. [23], a variety of economical, social, environmental, and legal risk factors significantly affecting PPP WTE incineration projects in China have also been identified in the current study (including environmental pollution risk, defective legal and policy making, opaque government decision-making, and insufficient and nonlicensed MSW supply) in spite of the rapid growth in WTE incineration implementation during the past decade.

Meanwhile, the rankings of the significance of these identified risk factors are different. In particular, due to rising public environmental awareness and an increasing emphasis on public health along with improvements in the economic conditions and living standards in China [14, 50], public opposition is increasingly becoming a key risk factor affecting the development of the PPP WTE incineration industry. At the same time, the ranking of MSW supply risk has relatively decreased since 2013. This is because the rapid urbanisation in China had resulted in a sharp increase in MSW generation and the central and local governments had issued a series of orientations and regulations to stress the significance of classification in the disposal of harmless and recycled MSW [74–76], by which the quality of MSW is significantly improved [10].

Moreover, some critical risk factors identified in the studies of Song et al. [4] and Xu et al. [23], such as technical risk, payment risk, and government credit risk, have gradually faded out in recent years. The possible reason is that some interim issues, such as government budget deficit and immature incineration technologies, have been gradually resolved with the continuous development of China's social and economic conditions. For example, the percentage of grate furnaces (advanced incineration technologies

Table 5: Comparative analysis of similar studies.

Profile	Song et al. [4]	Xu et al. [23]	The present study
Research methods	Expert interview and site investigation	Literature review and multiple cases studied using content analysis	Literature review and multiple cases studied using content analysis
Number of cases studied	6	14	35
Time range of events	Before 2008	2002–2012	2001–2016, with 80% after 2012
Criteria for case selection	All cases in operation	All cases in operation	About 2/3 of cases in operation
Risk factors identified	10 key risk factors	5 critical risk factors	18 risk factors with 5 high-frequency risk factors
Critical risk factors (high-frequency risk factors) discussed	Government decision-making risk	Insufficient waste supply	Public opposition risk
	Government credit risk	Environmental risk	Environmental pollution risk
	Legal and policy risk	Entry of nonlicensed waste	Government decision-making risk
	Technical risk	Lack of supporting infrastructure	Defective legal and regulatory system
	Contract change risk	Payment risk	MSW supply risk
	Environment risk		
	Public opposition risk		
	MSW supply risk		

[10, 77] and widely used in Europe, USA, and Japan) adopted in incinerators in China is about 64%, a figure predicted to increase constantly because of the localisation of the technology and policy support [10].

5. Conclusion

In light of the pivotal role that risk identification, analysis, and response play in the successful development of PPP WTE incineration projects, we conducted a multiple case study to identify the risk factors in China by drawing on the experience and lessons learn from the real-life risk events of 35 PPP WTE incineration plants through content analysis and expert interviews. The results provide a solid foundation for the further risk analysis, allocation, and response of PPP WTE incineration projects. Both researchers and practitioners of the PPP WTE incineration industry in China, including policy makers, WTE professionals, and academic researchers, may benefit from this study by referring to the identified risk factors in policy making, operating performance improvement, critical risk response, and so on. Thus, the present study is expected to shed light on their improvement in performance as well as the development and implementation of WTE incineration technologies in China's MSW disposal industry.

Based on a comprehensive analysis of the 35 selected cases, 18 risk factors affecting PPP WTE incineration projects in China are identified. The findings reveal that the performance of China PPP WTE projects is most affected by public opposition, environmental pollution, government decision-making, the defective legal and regulatory system, and MSW supply risks.

Although the current study contributes to the literature on the management of the PPP WTE industry and PPP infrastructure projects by identifying the risk factors affecting PPP WTE incineration projects in China, it also has some limitations that need to be addressed by further research. First, due to the limitation of case selection, there are undoubtedly other risk factors involved that are expected to be examined by further studies. Second, although multiple case studies were used in the current research, the identification of risk factors for each case was still based on the subjective judgment of experts, and future validation studies are needed using such quantitative or empirical research methods as case-based reasoning technologies and statistical analysis.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

The Moderating Effect of Guanxi on the Dynamic Capacity and Competitive Advantage of Chinese International Contractors

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With the active support of the national policy “One Belt and One Road” Initiative, Chinese contractors seized this historic opportunity to accelerate strategic globalization, and they gradually stood out in international construction projects owing to their low-cost advantage. However, despite China having large-scale contractors and wide-range business, compared to developed countries, a considerably large gap still exists. China is confronted with complex and changeable international projects filled with increasing competition. Thus, it is both a focus issue and a major task for Chinese international contractors, and many scholars, to consider how Chinese contractors can obtain and maintain long-term competitive advantages to improve their capabilities in response to dynamic environmental changes. Therefore, the objectives of this study are (1) to study the influence of the dynamic capability of Chinese contractors on competitive advantage in a project and (2) to explore the moderating effect of Chinese guanxi on the dynamic capability and competitive advantage of Chinese international contractors. This study primarily aimed at researching the impact of dynamic capacity of Chinese contractors on competitive advantage and the moderating effects of Chinese guanxi. The findings suggest that the environmental perception capability and the integration and coordination capability of the dynamic capability have a significant positive effect on the project competitive advantage; business guanxi positively moderates the relationship between the environmental perception capability and the competitive advantage. Business guanxi also negatively moderates the relationship between learning ability and competitive advantage, while political guanxi negatively moderates the relationship between the environmental perception capability and competitive advantage. This paper contributes to the construction management literature not only by providing empirical evidence on the dynamic capability and competitive advantage of Chinese contractors but also by expanding guanxi research. The results may also help Chinese contractors by providing strategic reform guidance and sustainable development in international construction projects.

1. Introduction

In September 2013, the president of China, Xi Jinping, proposed the “One Belt and One Road” (OBOR) initiative. With the active support of the national policy, Chinese contractors seized this historic opportunity to accelerate strategic globalization, and they gradually stood out in international construction projects owing to their low-cost advantage. Promotion of the OBOR not only mitigated the problem of overcapacity of the Chinese civil construction industry but also provided a competitive advantage to Chinese contractors. The number of overseas engineering contracts increased steadily with the development of improved relations with overseas businesses. According to a report in the Engineering News-Record (ENR), the number of Chinese contractors is the highest of the top 250 international contractors since 2008. A total of 65 Chinese contractors were listed in 2016, which was identical to that in the previous year. The total international revenue reached $93.67 billion USD, which was again the highest, and exceeded that earned in the previous year by 4.5%. Even in an environment where the overall revenue from the overseas market was decreasing, Chinese contractors maintained stable growth, demonstrating the gradually increasing strength of Chinese international contractors [1, 2]. However, despite China having large-scale contractors and wide-range business, compared to developed countries, a considerably large gap still exists. China is confronted with complex and changeable international construction projects filled with increasing competition. Thus, it is both a focus issue and a major task for Chinese international contractors, and many scholars, to consider how Chinese contractors can obtain and maintain long-term competitive advantages to improve their capabilities in response to dynamic environmental changes.

Traditional research on business capabilities emphasizes the application of current resources and abilities. However, traditional theories gradually prove to be lacking in explanatory power under the revolution of the market environment [3–5]. Typically, with the pronounced change of the market and thriving new technology, more companies realize the importance of gaining advantages over the competition through the improvement and revolution of their abilities. The theory of dynamic capability was created considering the above background [6], which thoroughly explains how businesses could gain advantages in competition in dynamic environments, and it has become the dominant theory in the research of competitive advantages in the field of strategic management. Therefore, further exploration of the relationship between dynamic capacity and competitive advantage of Chinese international contractors is needed.

Additionally, research has discovered that it is not the ability of the Chinese contractors which is to blame for the failure of completing many international construction projects smoothly, but the disoperation in managing relationships among stakeholders [7, 8]. During the process of market development, it is common practice for Chinese contractors to improve their operations by building external relationships when faced with various difficulties in the international environment, such as excessive prices. As a unique character of the Chinese society, the Chinese *guanxi*, which has increasing broad influence, is already a new tool for contractors in solving problems and promoting competitive advantages [9]. On the contrary, according to Forbes, the Chinese guanxi has been overestimated, and blindly taking it as a shortcut will lead to nothing but failure [10]. Based on the above discussion, how the Chinese guanxi affects the advantages of competition of Chinese contractors deserves further research.

Many scholars believe that dynamic capabilities are the key to competitive advantage [11–14], while some argue that dynamic capabilities do not manifest characteristics of heterogeneity and, thus, cannot be a source of competitive advantage [15]. They believe that the role of dynamic capabilities is limited [16] and indirect [17]. In response to such paradoxes in the impact of dynamic capabilities on competitive advantage, researchers have not yet provided a compelling explanation for the effect of the Chinese guanxi on the relationship between dynamic capabilities and competitive advantage. The gaps in the extant literature on dynamic capacity and competitive advantage of Chinese international contractors may stem from a failure to develop a theoretical model that enables the exploration of how dynamic capacity's influence on competitive advantage is integrated with Chinese guanxi's competitive advantage. Many researchers claim that the Chinese guanxi plays an important moderating role between firm capabilities and performance in China [18]. Guanxi has been identified as part of Chinese culture, related to the management of firms [9]. Gu [19] and Luo [20] argue that the Chinese guanxi is a lasting social relationship and network, profoundly influencing the competitive advantages of firms. Moreover, the Chinese guanxi is considered to be a type of social capital and network, which creates benefits like information, influence, control, and power [19, 20].

The significant effects of the Chinese guanxi on competitive advantage have been substantially discussed in the literature, but there is limited understanding of how it affects Chinese contractors' abilities to gain dynamic capacity and competitive advantage. This is because most prior research has investigated dynamic capacity as a single-independent variable and associated it with competitive advantage without considering its process-dependent nature. Previous researchers have not fully understood how Chinese guanxi could gain dynamic capacity from different host country contexts. Hence, we integrated the Chinese guanxi as a moderator and investigated its interactions with dynamic capacity and competitive advantage.

Therefore, in view of the turbulent and changing international competition environment faced by Chinese contractors and the unique social and cultural background of China [10], the objectives of this study are (1) to study the influence of the dynamic capability of Chinese international contractors on competitive advantage in a project and (2) to explore the moderating effect of Chinese guanxi on the dynamic capability and project competitive advantage of Chinese international contractors.

2. Literature Review

2.1. Dynamic Capability and Competitive Advantages. The concept of dynamic capability was first proposed by Teece and Pisano [21], pointing out that the dynamic capability is the ability of an enterprise to carry out the construction, integration, and reconstruction of internal and external abilities in order to quickly respond to changes of the environment [22]. Protogerou et al. [23] proposed that dynamic capability is the behavior guidance of the transformation, upgrading and reconstructing the core competence for an enterprise, and is an important source of sustainable competitive advantage. This paper argues that dynamic capability is a strategic practice, in which firms can integrate and restructure resources and capabilities within and outside the enterprise in order to gain sustainable competitive advantage.

The theory of dynamic capabilities is developed based on the original theory of the competitive advantage [11–14]. It is capable of combining the external environment with internal resources, emphasizing the dynamic improvement of resources and the ability of the enterprises responding to the environment. It can also fully explain the source of the competitive advantage of enterprises and adapt to the complicated and dynamic environment, fully and effectively guide the enterprises to obtain in the current dynamic environment, and maintain a competitive advantage. Therefore, this paper adopts the theory of dynamic capabilities as the main theoretical basis.

There are many theories and empirical studies on the relationship between dynamic capabilities and competitive advantages, but the perspectives, methods, samples, and conclusions of different researches vary from each other. Many studies have shown that dynamic capabilities and competitive advantage are correlated [11, 12, 24], among which most scholars believe that the dynamic capability has a positive effect on the relationship between the direct competitive advantages [13, 14].

2.2. Chinese Guanxi. Guanxi, as a kind of special Chinese culture [9], is closely related to the management of the enterprise, especially for the international construction project, and the importance of the Chinese guanxi penetrates into various stages of the project. The Chinese guanxi, as an informal system, compared with the formal system, such as law and policy, has an impact on the performance of enterprises and then affects the competitive advantage of enterprises [18]. Therefore, this paper introduces the Chinese guanxi into the study of competitive advantage.

There are many definitions about the Chinese guanxi, but so far there is no uniform standard. Davies et al. [25] define the Chinese guanxi as an interaction between social networks and members of society, which is equivalent to an infinitely repetitive reciprocal activity among groups of people who know it. Fan [26] points out that the Chinese guanxi is a way of using personal relationships to seek potential economic benefits. The Chinese guanxi refers to interpersonal relationships, whereas Western style relationships refer to the relationship among organizations [27]. Li Xin [28] believes that the Chinese guanxi is limited not only to personal contacts, but also among enterprises. The Chinese guanxi is a mutually beneficial responsibility relationship between an enterprise and its partners, which enables the enterprise to obtain resources and information through continuous cooperation and mutual communication [29]. Gu et al. [19] and Luo et al. [20] argue that the Chinese guanxi is a lasting social relationship and network that enterprises use to exchange support for organizational goals and exerts certain influence on competitive advantages. To sum up, the Chinese guanxi is a unique feature of Chinese social culture, which penetrates all aspects of personal and organizational communication, and social interaction, and it has become a way for Chinese enterprises to conduct business, handle problems, and obtain information.

There are many theories of the Chinese guanxi, and scholars in many fields, such as economics, sociology, and management, have explored the theory of Chinese style relations in their respective fields. Among them, the common ones are transaction cost theory, social exchange theory, social capital theory, institutional theory, resource dependence theory, and so on [30]. Transaction cost theory holds that reduction of transaction costs is the most fundamental motive force for interorganizational cooperation and relationship building [31, 32]. The resource dependence theory believes that the survival and development of the organization and the competitive advantages depend on the external environment and organizational resources, and the long-term close relationship is an important means to solve environmental uncertainty and the lack of resources [33, 34]. For the development of overseas market of international contractors, in order to obtain and maintain sustainable competitive advantages, they should, on one hand, reduce costs and improve efficiency and acquire and master more unique resources, and on the other hand, they should fit the transaction cost theory [31, 32] and resource dependence theory [30]. Therefore, the transaction cost theory and resource dependence theory are here to explain the influence of the Chinese guanxi on the competitive advantage.

Through the search and reading of a large number of relevant literature at home and abroad, it can be found that none deals with the relationship between dynamic capabilities, Chinese guanxi, and competitive advantages. As a result, this paper will introduce the Chinese guanxi into the study of competitive advantage, as a moderator of dynamic capability and competitive advantage, which is of pioneering significance.

3. Research Hypotheses and Theoretical Model

3.1. Dynamic Capacity and Competitive Advantage. According to a wide range of existing literature, different scholars choose different dimensions to study dynamic capacity. Teece [35] divides dynamic capacity into three dimensions from the angle of opportunity: the ability to perceive opportunities and threats, the ability to seize opportunities, and the ability to reconstruct assets. Protogerou et al. [23] measure dynamic capacity considering coordination/integration capability, learning ability, and the capability to cope with strategic competition. Wilden and Gudergan [36] examine dynamic capacity from the two dimensions of opportunity perception and opportunity reconstruction. They consider Chinese internal contractors' resources, businesses, and strategy in response to changes in the international market, and the learning of advanced construction technology and management experience, so that Chinese internal contractors can overcome the threat of competitors.

This research will measure the dynamic capacity of contractors from three aspects: environmental perception ability, learning ability, and integration and coordination capability.

3.1.1. Environmental Perception Ability and Competitive Advantage. Environmental perception ability is the ability of enterprise decision-makers and ordinary employees to discern market opportunities and risks by searching, merging, and filtering information, which is unable to create the market value directly but is a prerequisite for creating the value [37]. Some empirical studies have proven that environmental perception ability enables enterprises to better respond to changes in market needs and expectations, to obtain long-term competitive advantage and super profit [38], and to quickly perceive and discern the nature of, and opportunities arising from, market environmental changes so as to provide enterprises with a potential sustainable advantage [39]. Under the circumstances of a fickle international engineering market, to maintain a sustainable competitive advantage, keen environmental perception ability is essential for rapidly discerning opportunities and risks resulting from environmental changes, managing to seize opportunities, and dealing with threats. Thus, we propose the following hypothesis:

> Hypothesis 1: Chinese international contractor's environmental perception ability has a positive impact on project competitive advantage.

3.1.2. Learning Ability and Competitive Advantage. Referring to the ability of an enterprise to acquire external and new knowledge, to integrate external and new knowledge with internal and existing knowledge, and to create new knowledge, learning ability is one of the main measures ensuring the renewal and evolution of enterprise capacity [17]. Chinese international contractors can learn advanced construction techniques and managerial experience from competitors or partners and the development model and business strategy from top-notch international contractors. Presently, as Chinese contractors are confronting a rapidly changing international engineering market, their initial accumulated experience and knowledge may become out of date and lose competitiveness. However, a quick yet efficient learning ability enables them to update and advance enterprise strategies, organizational structures, and so on. Thus, we propose the following hypothesis:

> Hypothesis 2: Chinese international contractor's learning ability has a positive influence on project competitive advantage.

3.1.3. Integration and Coordination Capability and Competitive Advantage. Integration and coordination capability constitutes an integral part of dynamic capacity. Using internal integration and external coordination of resources, enterprises can enhance the strategic value of existing resources and capabilities and promote strategic decision-making and reform to cope with changes in the external environment [40]. The construction process of a project is in effect a process of resource integration and coordination, during which the smooth advance of each link relies on the effective integration and coordination of various resources and tasks, and the internal and external resources need to be readjusted once the reality deviates from the plan. To establish and maintain a competitive edge, it is indispensable for enterprises to make timely and accurate judgments of a situation based on environmental changes. Subsequently, they must effectively integrate resources and actively adjust strategies and, finally, develop products and services satisfying market demand. Thus, we propose the following hypothesis:

> Hypothesis 3: Chinese international contractor's integration and coordination capability has a positive effect on project competitive advantage.

3.2. The Moderating Effects of Chinese Guanxi. The Chinese guanxi is a mutually beneficial responsibility relationship between an enterprise and its partners, which enables the enterprise to obtain resources and information through continuous cooperation and mutual communication [29]. The Chinese guanxi is a lasting social relationship and network that enterprises use to exchange support for organizational goals and exerts a certain influence on competitive advantages [19, 20]. Dynamic capacity enables contractors to compete by comprehending client preferences and creating and managing long-lasting relationships with owners, designers, and suppliers. The process of acquiring and comprehending owners' needs requires firm boundary agents to have empathetic orientation, that is, the ability to view a situation from an owner's perspective. Empathy is valuable in nurturing guanxi, and members in the guanxi network should exhibit empathy toward one another [41]. Thus, contractors with a high dynamic capacity are likely to have competent personnel who are good at developing close guanxi with key stakeholders. At the same time, the process of creating and managing long-lasting relationships entails that boundary personnel have more communication, negotiation, and coordination skills, which may also be helpful for cultivating interpersonal connections. Therefore, in the international construction project in which guanxi is important for project success, contractors with greater dynamic capacity are better able to exploit guanxi networks and, thus, obtain a competitive advantage.

Regarding the dimensions of the Chinese guanxi, Peng and Luo [42] divide the Chinese guanxi into business guanxi and political guanxi based on the particularity of the Chinese society and differences among external entities. The distinction between these two types of relations is that business guanxi is horizontal (equal relations), yet political guanxi is vertical (the leader-member relations, that is, the relations between superior and subordinate). This manner of division has been recognized by many scholars [9, 20, 43] and has been widely adopted. This research also adopts this manner of division and divides Chinese guanxi into the two dimensions of business guanxi and political guanxi. When it comes to the specific research background of the construction projects studied, business guanxi mainly refers to the relations with owners, supervisors, and suppliers, while political guanxi refers to the relations with government leaders, the relevant government departments, and government officials.

Thus, we suggest that the impact of dynamic capacity (environmental perception ability, learning ability, integration, and coordination capability) on competitive advantage is contextually moderated by the Chinese guanxi (business guanxi and political guanxi).

3.2.1. The Moderating Effect of Business Guanxi. Establishing and sustaining business guanxi allow enterprises to have more comprehensive access to information and to perceive the trend of the changing market environment better. In this way, timely measures can be taken to avoid risks and reduce losses amid environmental changes. As the transaction cost theory states, the higher the transaction uncertainties are, the higher the transaction cost is [44]. However, business guanxi can significantly reduce the impact of environmental uncertainties, thereby reducing transaction costs, increasing profits, and enhancing competitive advantage. The resource dependence theory states that an organization must interact with the environment it depends on to hold the initiative over its competition [45]. Establishing business guanxi provides enterprises with an interactive relations network, and those holding the initiative can gain a higher competitive advantage.

Establishing and sustaining business guanxi promote exchange and communication among different enterprises and facilitates the establishment of a good learning atmosphere, in which one makes progress by drawing upon another's experience, thus laying a solid foundation for the future growth of enterprises. In line with the transaction cost theory, relations are transferable, long term, and intangible assets [46] that enable enterprises to enhance learning abilities and gain competitive advantage. According to the resource dependence theory, relations enable organizations to bring forth new ideas, contribute to the transfer and overflow of knowledge, and promote cooperation among organizations in exerting external control over other organizations and, thus, enhance a unique competitive advantage.

Establishing and sustaining business guanxi allow enterprises to have more resources indirectly and promote enterprises to optimize the allocation of existing and potential resources. Based on the transaction cost theory, the higher the asset specificity is, the higher the transaction cost is [44], but business guanxi reduces the difficulty in acquiring specific assets and, therefore, significantly decreases transaction costs and increases competitive advantage. Considering resource dependence theory, the survival and growth of organizations need to draw on resources from surroundings [47], while business guanxi happens to afford effective access to resources.

Thus, we propose the following hypotheses:

Hypothesis 4a: the positive relationship between environmental perception ability and competitive advantage is stronger when business guanxi is at a higher level.

Hypothesis 4b: the positive relationship between learning ability and competitive advantage is stronger when business guanxi is at a higher level.

Hypothesis 4c: the positive relationship between integration and coordination capability and competitive advantage is stronger when business guanxi is at a higher level.

3.2.2. The Moderating Effect of Political Guanxi. In the view of transaction costs theory, because of the chronicity and reciprocity of a relation, an enterprise requires a relatively high cost to establish and maintain relations [48]. However, it is difficult to determine the actual effects of such a relation on competitive advantages. According to Luo et al. [49], a high-degree of political guanxi has substantial hidden danger to the subsequent progress of a project. To maintain a high level of political guanxi, the project leader or the one in charge of the enterprise may have less time and energy to pay attention to the changes in the external environment. Thus, they may somewhat ignore whether the development of the enterprise can adapt to the changes in the external environment, consequently reducing the abilities of the enterprise or project to resist risks. Resource dependence theory believes that acquiring resources from the external environment, being interdependent with the environment and striving for the balance of relations, can avoid dependence on the opportunities brought by markets and technologies [19]. Excessive pursuit of political guanxi may have the opposite effect—losing opportunities brought by the acquisition of markets and technologies.

Transaction costs theory demonstrates that relations are transferable, long term, and invisible assets [46]. However, political guanxi has features of being personal and untransferable. Once there are changes in the political party, an enterprise may, in a very short time, lose their political guanxi network established by prior hard work. Resource dependence theory indicates that establishing a good relationship with resource providers allows us to analyze and control the external environment with initiative rather than passively adapting to the environment, which can reduce dependence on the environment. However, political guanxi cannot be controlled by enterprises. Very often the government will, through an interrelationship, encourage the enterprise to invest in some projects which are very important for it, such as construction aid projects, which are of very high opportunity cost for contractors and do not conform to their development strategies. To maintain good relations, contractors often, regardless of profits and costs, devote much time and effort to establishing a stable political guanxi network, which may come at the cost of giving up self-development [29, 50].

Transaction costs theory states that the higher the transaction frequency is, the higher the transaction cost will be [29, 50]. The maintenance of political guanxi requires a higher deal cost, which will affect one's competitive position. To maintain a high level of political guanxi, the person in charge of a corporation and project is likely to spend less time and energy in focusing on the development strategies and management standards of corporations, which will affect the plan and implementation of the resource integration of a corporation or project. Resource dependence theory states that the survival and development of organizations requires the consumption of resources from the surrounding environment. Although political guanxiship has provided a way to gain resources, contractors are likely to be forced to receive some unwanted material for the maintenance of the mutual benefits from political guanxi, which has dramatically increased the operating costs of corporations. Thus, we propose the following hypotheses:

Hypothesis 5a: the negative relationship between environmental perception ability and competitive advantage is stronger when political guanxi is at a lower level.

Hypothesis 5b: the negative relationship between learning ability and competitive advantage is stronger when political guanxi is at a lower level.

Hypothesis 5c: the negative relationship between integration and coordination capability and competitive advantage is stronger when political guanxi is at a lower level.

3.3. Theoretical Model. Based on the above assumptions, we can construct the theoretical model of this study, as shown in Figure 1. The model constructed in this paper is a trans-level regulation model, in order to examine how the relationship between high-level constructs (dynamic ability) and low-level outcome variables (competitive advantages) can be regulated by another low-level construct (Chinese guanxi).

4. Research Method and Design

4.1. Econometric Model. In this study, the multivariate linear regression analysis and the multivariate regulatory regression analysis are used as the primary research methods [51]. The multivariate regulatory regression analysis is suitable for the model in which both the main effects and regulatory effects exist simultaneously. Moreover, it can analyze whether the model is better than the one with the main effects after adding adjustment effects [52]. To ensure that our hypothesized relationships were under better-controlled environments, the study included six variables to control for potential factors that might correlate with the hypothesized determinants or dependent variable. This study includes the state-ownership of the contractor, the size of the contractor, the firm age, the project type, the contract budget of the project, and the GDP of the host country as control variables.

Accordingly, this paper establishes the following regression equation:

$$\begin{aligned}\text{Com} = {} & \alpha + \gamma_1\text{state} + \gamma_2\text{size} + \gamma_3\text{age} + \gamma_4\text{tran} + \gamma_5\text{budget}\\ & + \gamma_6\text{gdp} + \beta_1\text{Env} + \beta_2\text{Lea} + \beta_3\text{Int} + \beta_4\text{Bus} + \beta_5\text{Pol}\\ & + \beta_6\text{Env} * \text{Bus} + \beta_7\text{Lea} * \text{Bus} + \beta_8\text{Int} * \text{Bus}\\ & + \beta_9\text{Env} * \text{Pol} + \beta_{10}\text{Lea} * \text{Pol} + \beta_{11}\text{Int} * \text{Pol} + \varepsilon,\end{aligned} \tag{1}$$

where the dependent variable, Com, is the competitive advantage of the project; α is a constant; $\gamma_1 - \gamma_6$ are the coefficients of the controlled variable; $\beta_1 - \beta_3$ are the coefficients of the independent variable; $\beta_4 - \beta_5$ are the coefficients of the moderator; $\beta_6 - \beta_{11}$ are the coefficients of the cross item; and ε is a disturbance variable. The first independent variable, Env, is the environmental perception ability; the second independent variable, Lea, is the learning capability; the third independent variable, Int, is the integrating and coordinating capability. The first moderator, Bus, is the business guanxi; the second moderator, Pol, is the political guanxi. To prevent spurious regression and to ensure that the tests are better controlled for the environment, the state-own of the contractor, the size of the contractor, the age of the contractor, the project type, the contract budget of the project, and the GDP of the host country, six variables were thus employed as control variables in our research.

This equation can not only test the impact of the dynamic capability of Chinese international contractors on the project's competitive advantages but also involve the moderating effect of guanxi on the dynamic capability and competitive advantage of Chinese international contractors.

4.2. Data. This study used a literature review, in-depth interviews, and a questionnaire survey for data collection [53]. Data collection was conducted in two stages. First, in-depth interviews were conducted with six senior project managers, market managers, contract managers, purchase managers, contract consultants, and general managers from Chinese international contractors between March 2016 and June 2016. The interviews served as an a priori test, and we designed and pretested a questionnaire including all constructs of interest for measuring the model variables. Second, we applied a cross-sectional survey to collect primary data from questionnaires which were sent to Chinese international contractors.

According to the study's needs, the respondents were middle or senior managers who had been working in the same projects for over one year to ensure a full understanding of the project, which helped to enhance data quality. The questionnaire was completed by the students of MEM (Master of Engineering Management), alumni who have experience with international contractors. In China, MEM students are incumbents in management positions in firms who work in firms on weekdays and receive on-the-job training during weekends, so they are quite familiar with what happens in their projects. Questionnaires were sent to the students of MEM and alumni through e-mail and the Internet. The MEM students and alumni were expanded by "snowball," that is, by drawing and organizing the sample gradually through the interviewee's recommendation and re-recommendation [54, 55]. Data collection was conducted from June 2016 to January 2017. In total, 88 questionnaires were returned with 57 being valid. The collection ratio of valid questionnaires is 64.77%.

The sampling frame included those international projects from the major construction projects conducted overseas during the past five years, such as transportation, building, petroleum, energy, and hydraulic engineering overseas. Nearly 93% of the respondents were male, and

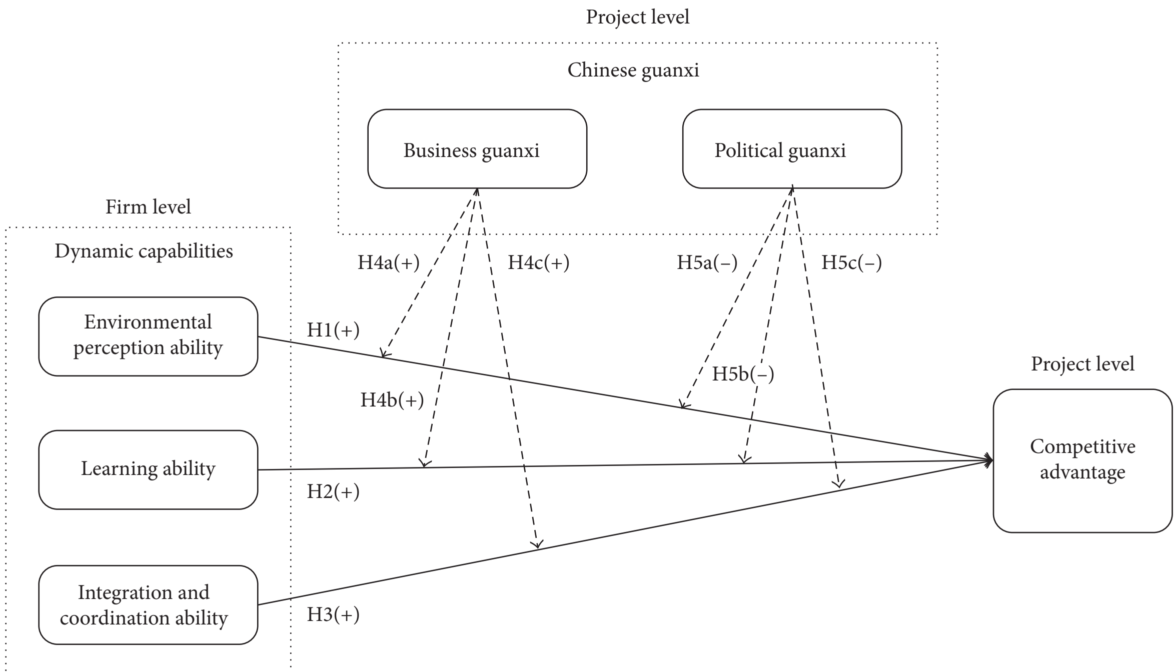

Figure 1: Theoretical model of the study.

approximately 50.9% were between 31 and 40 years old, about 52.6% of respondents had worked on international construction projects for a period of four to ten years, and almost 31.6% hold a postgraduate qualification. Among the respondents, senior managers accounted for 47.4% of the respondents and project level managers accounted for 38.6%. As data acquisition in international projects is somewhat difficult, the literature sample in similar research in the field of international projects is only 45 [56], and regression analysis only requires a minimal sample of 30 [57–59]; although the sample is not very large, the number of valid questionnaires has met the requirements of research.

After sorting out the valid questionnaires, the study classified the basic information of the sample into enterprises, projects, and people who filled out the questionnaire. The projects in the questionnaire were distributed in 32 nations or regions in Asia and Africa (over 90% of the total number of the sample), Europe, Oceania, and North America. There were a great variety of diverse projects, including transportation, housing, petrochemicals, energy, and water conservancy. Transportation and housing account for 64.9% of the total number of samples, which is more than half of the sample number. The sample information is shown in Table 1.

Table 1: Descriptive statistical analysis of the sample distribution projects ($N = 57$).

Item	Type	Frequency	Percentage
Country type of project	Low-income countries	3	5.3
	Low- and middle-income countries	15	26.3
	Middle and higher income countries	17	29.8
	High-income countries	22	38.6
Project area	Asia	34	59.6
	Africa	19	33.3
	Europe	1	1.7
	Oceania	2	3.5
	North America	1	1.7
Project type	Transportation	18	31.6
	Building	19	33.3
	Power	7	12.3
	Petroleum	7	12.3
	Hydraulic engineering	4	7.0
	Others	2	3.5
Project delivery method	EPC	26	45.7
	DB	10	17.5
	PPP	6	10.5
	PC/C	13	22.8
	Others	2	3.5
Project construction phase	Biding	9	15.8
	Construction	35	61.4
	Completed	13	22.8

4.3. Measurement of Variables. Concerning previous studies, the authors developed a multiple-item scale of variables. Because the related literature is in English, we made an effort to translate the questionnaire comprehensively and critically.

In the context of Chinese international contractors, this study employs a survey method for data collection. An extensive literature review was the basis for developing an initial list of items to measure the components of the concepts. Then, to revise the measurement items, this study carried out a pretest with six project managers from six different contractors working in overseas construction projects. For the pretest, the study first chose six project managers from six different contractors working on international construction projects. Moreover, the next step was to conduct a pilot study involving five contractors (each with one respondent) to determine the efficiency of the questionnaire. Finally, this study checked item-to-total correlations to refine measurements.

Responses were scored on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) [13, 60].

4.3.1. Measurement of the Dependent Variable and Independent Variables

(1) Competitive Advantage. Most researches adopt public archive data to measure competitive advantage, among which ROA and Tobin's Q are popular proxies [13]. For construction contractors, on one hand, to get such series data is somewhat difficult for the lack of such database; on the other hand, construction contractors may not be willing to provide their financial data. According to the argument that competitive advantage can be measured by financial indicators and nonfinancial indicators [13], this study measures competitive advantage by questions, reflected by 3 indicators, including profit, technology, and social appraisal [61, 62].

(2) Environmental Perception Ability. This variable is the ability of an enterprise to dig for market opportunities by acquiring external market information through a comprehensive analysis of its own development status and external environment. Environmental perception ability is a two-step process, that is, to search for market information and to analyze market information. Neill et al. [63] have proposed four measures of environmental perception, namely, competitor-oriented, customer-oriented, "product-oriented, and macroenvironment-oriented." Li and Liu [13] have proposed six design indicators for environmental perception ability, namely, to perceive environmental changes ahead of competitors, meet regularly to discuss market needs, agree on understanding of the impact on internal and external environment, understand the major potential opportunities and threats, have a sound information management system, and have a good observation and judgment abilities. Through the above analysis, we can see that the external environment the company is facing includes competitors, customers, industries, and so on, and it is even more so for international contractors who undertake overseas projects. Not only does the market environment cover a wide range of areas, it also involves a variety of stakeholders. Therefore, the environmental analysis for international contractors must be comprehensive and multidimensional. Based on this, this research divides the measurement indicators of the environmental perception ability for Chinese international contractors into the following five aspects.

(3) Learning Ability. This variable reflects the ability of an enterprise to use internal and external information, knowledge, and technology and apply to practice. The learning ability of Chinese international contractors mainly reflects in three levels, that is, individual level, project level, and enterprise level. As a project-oriented enterprise, many of its knowledge and experience are accumulated during the implementation of the project. In order to cultivate the learning ability of the enterprise, it is necessary to create an atmosphere that encourages employees to learn, secondly, to be able to accomplish effective knowledge sharing among employees, and the most important is to effectively apply the acquired knowledge to practical work and play a role in internal management and external services. Todorova and Durisin [64] pointed out that learning ability is the ability of an enterprise to discover new knowledge, exchange and share new knowledge, and apply it to commercial activities. Therefore, the measurement of learning ability is mainly consistent with the above description. Combined with the studies of Zahra and George [65] and Li [66] on the measurement of learning ability, this paper designed five indicators.

(4) Integration and Coordination Ability. This variable is the ability of an enterprise to reconstruct internal and external resources and capabilities. It reflects in all aspects of the enterprise's daily operations, such as new products' development, strategic decision-making, strategic cooperation, and strategic transformation, and it has an irreplaceable role for the development and even survival of enterprises [67]. Li and Liu [13] measured the integration and coordination ability from the aspects of decision-making and implementation and designed the following indicators, namely, "to make strategic decisions in time, effectively implement strategic changes, and have good cooperation with other enterprises." Hao [62] believes that the integration and coordination ability is divided into internal integration and external coordination and designs the following indicators "awareness of consensus among various departments on strategic objectives, frequent cooperation with other enterprises in developing markets, and so on." This paper believes that except effectively reshaping of internal and external resources, it should also be able to make adjustments quickly and in time and maintain adjustability at all times to respond to environment changes. Based on this, this paper has designed the following six indicators, as shown in Table 2.

(5) Business Guanxi. In recent years, researches on the Chinese guanxi have emerged in an endless stream, and many scholars have also attempted to conduct in-depth studies on guanxi empirically. As mentioned in the previous literature review, most scholars classify it into two dimensions, business guanxi and political guanxi. Wu and Chen [68] designed the indicators of business guanxi as "good interpersonal relationships with suppliers, customers, and distributors." Liu et al. [69] designed the indicators of business guanxi as "to have strong capabilities to build good relationships with customers, suppliers, and competitors." Wang [70] divided business guanxi into relationships with suppliers, customers, research institutes, and other stakeholders, and each type of relationships includes "the establishment of long-term trust and ability to communicate information in time." Based on

Table 2: Measurement of variables.

	Item	Cronbach's α	KMO
Dependent variable			
Competitive advantage	(i) Compared with projects of the same type, the profit of this project margins higher (ii) Compared with projects of the same type, this project meets with more technical difficulties (iii) Compared with projects of the same type, this project wins higher social appraisal	0.507	0.577^{***}
Independent variables			
Environment perception ability	(i) The company can grasp the newest information of competitors (ii) The company spends a lot of efforts and time in gathering biding information (iii) The company can detect and grasp industry trends timely (iv) The company is ignorant about the development of new technology in international market (inverse problem) (v) The company can detect and seize market opportunity properly	0.723	0.781^{***}
Learning ability	(i) The company encourages employees to acquire knowledge through various means (ii) The company does not encourage sharing knowledge among employees (inverse problem) (iii) The company can apply new knowledge to work quickly and effectively (iv) The company cannot provide innovative services to meet the needs of owners (inverse problem) (v) The company has taken a reform in its management	0.689	0.739^{***}
Integration and coordination	(i) Each department of the company has agreement on the company's strategic goal (ii) Each department of the company cooperates frequently (iii) The company often makes strategic alliance with other companies (iv) The company can adapt its development to changes in international environment (v) The company changes its strategy slower than its competitors (inverse problem) (vi) The company can adjust its role accurately according to the environmental change in international project market	0.864	0.852^{***}
Business guanxi	(i) The company has a bad relationship with owners (inverse problem) (ii) The company can communicate well with owners (iii) The company builds a good relationship with supervisors (vi) The company can communicate well with supervisors (v) The company has a good relationship with suppliers (vi) The company does not communicate well with suppliers	0.831	0.839^{***}
Political guanxi	(i) The company maintains a good relationship with the host country (ii) The company can obtain the information in relation to the project timely (iii) The company does not receive financial support or preferential policies from the government of the host country (inverse problem) (iv) The staffs of the company have a good interpersonal relationship in their personal life with government officers in the host country	0.753	0.688^{***}

$^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$ (two-tailed).

the above points of view and taking into account the large number of stakeholders, this paper selected three major stakeholders, that is, the owner, supervisor, and supplier, and included them into the design of the questionnaire. Based on this, this paper has designed the following six indicators.

(6) Political Guanxi. There are also many indicators designed for political guanxi. Wu and Chen [68] designed the indicators of political guanxi as "good interpersonal relationships with government officials and relevant government departments." Fan [71] designed the indicators of political guanxi as "to establish good relations with influential government officials and project-related government officials and to take actions to maintain good relations with government officials." Wang [70] designed such items as "Enterprises can timely obtain government information related to business operations, maintain good relations with relevant government departments, and acquire government support or funds." In summary, this paper designed four indicators.

Based on the previous research as well as the actual situation of this study, the results of the measurement for the three dimensions of dynamic capacity, the two dimensions of guanxi, and the competitive advantage are shown in Table 2.

Cronbach's alpha measures the reliability of the measurement. A higher value of Cronbach's alpha indicates a higher degree of reliability. The result of the measurement is not reliable and thus unacceptable if the value of Cronbach's alpha is less than 0.5; the result is acceptable if the value is greater than 0.5. When the value is greater than 0.7, the measurement is very reliable [72–74].

The structural validity of the measurement is tested by the exploratory factor analysis (EFA). Specifically, the measurement is required to pass the KMO's sample test by

SPSS and Bartlett's spherical test. The KMO's sample test demonstrates the partial correlation between variables. Generally speaking, the result of the measurement will meet requirements if the value of KMO is greater than 0.5 [75, 76], and the result will be better if the value is greater than 0.6.

As the data in this table show, both the reliability and the structural validity of the measurement have met the requirement with the value of Cronbach's alpha being greater than 0.5 and the value of KMO being greater than 0.5.

4.3.2. Control Variables. The study included six variables to control for potential factors, which are as follows:

(1) *The nature of enterprise*: The nature of enterprise refers exclusively to the ownership of enterprise. In terms of the ownership, China's international contractors can be divided into two categories, namely, the state-own enterprise and the private-run enterprise. Since Chinese government plays a prominent role in leading China's economy, many international engineering projects participated by Chinese enterprises are in fact the product of government's foreign activities. The government has assisted Chinese project industry with a lot of support and convenience, so enterprises of different ownership may have a different performance in acquiring project orders or undertaking project construction. Thus, this study takes the nature of enterprise as a variable into the measurement. In detail, the nature of enterprise is set as a dummy variable whose value ranges from 1, if the contractor is state-owned, to 0, otherwise [77, 78].

(2) *The scale of enterprise*: The scale of enterprise is taken as determined by the number of its employees [13, 79]. It reflects the concentration of labor force, means of production, and operating status in an enterprise, and it is usually assessed by the number of full-time employees, total assets, annual operating income, and so on. In general, the large-scale enterprises have more abundant human and financial resource, have more advanced technology, and can undertake more larger projects with larger scale; consequently, they often share a dominant position in the project industry. In contrast, the small and medium enterprises receive less investment, have less resource, and are more vulnerable to environmental change. The scale of enterprise has a more distinct influence on the international contractors. In this paper, the natural logarithm of the number of full-time employees is used to measure the scale of enterprise.

(3) *The enterprise's age*: The enterprise's age usually refers to the number of years after the enterprise was founded; namely, it refers to the enterprise's natural age [13, 79]. Generally, an enterprise may undertake more projects, have more experience, and hence have a better performance in undertaking new projects if it was established earlier and has operated longer.

(4) *Project type*: The international engineer contracting market covers dozens of industries and consists of numerous types of projects. Overall, as the traditional dominant industries, house building, industrial/petrochemical, and transportation account for nearly 80% of the annual market share, making their role in the engineer contracting industry seemingly unshakeable. Among these three types, transportation has grown rapidly and is accountable for the most significant market share. Indeed, China's international contractors have performed better in transportation in recent years, compared with other types of projects. Thus, project type is used as a dummy variable in the measurement whose value ranges from 1, if the project is transportation, to 0 [79, 80].

(5) *The contract amount of project*: The contract amount is the price of the project negotiated in the project contract. In addition to the type of project, the contract amount also indicates the scale and difficulty of the project [81]. In this paper, the value of the contract amount as a variable is the logarithm of the contract amount.

(6) *The GDP of target country*. The economic condition of the country where the project is constructed will relatively affect the project in ways such as through resource allocation [81]. All data of GDP (2015) used in this paper are from the World Bank (World Bank Group, WBG) database and have been taken as a logarithm. Note that Iran's GDP data in 2015 are missing, as are their 2014 GDP data.

5. Results

5.1. Robustness of OLS Regression Analyses. OLS (ordinary least squares) multiple linear regression analysis was used to test our hypotheses. OLS estimators are the best linear unbiased estimators (BLUE) [82]. Several regression diagnostics were taken to ensure that major OLS assumptions were satisfied. Specifically, the study tested whether there were multicollinearity problems, specification errors, or heteroscedasticity.

First, since the suspected significant correlations were found among some regressors as shown in Table 3, variance inflation factor (VIF) tests against each regressor were performed to test the no-multicollinearity assumption for OLS. If the correlation coefficient between the two variables is higher than 0.6 in significance, there may be an existing issue of multiple collinearities between them, and the VIF test [83] is required. It can be seen from the table that the correlation coefficients between the variables are all smaller than 0.6. So, there is no issue of multiple collinearities.

Second, the Ramsey RESET test [84] was performed to test specification errors such as omitted variables and the nonlinearity of functional form. When the significance of the F value in the RESET test is greater than 0.05, this indicates that there is no missing variable in the model [85].

Table 3: Means, standard deviations, and correlations of regression variables.

	Variable	Mean[a]	SD[a]	1	2	3	4	5	6	7	8	9	10	11	12
1	Com	3.28	0.80	1.00	—	—	—	—	—	—	—	—	—	—	—
2	Env	3.78	0.86	0.32**	1.00	—	—	—	—	—	—	—	—	—	—
3	Lea	3.95	0.87	0.02	0.29**	1.00	—	—	—	—	—	—	—	—	—
4	Int	3.86	0.76	0.19	0.16	0.50***	1.00	—	—	—	—	—	—	—	—
5	Bus	4.10	0.71	0.25*	0.25*	0.25*	0.48***	1.00	—	—	—	—	—	—	—
6	Pol	3.34	1.14	0.03	0.08	0.02	0.33**	0.32**	1.00	—	—	—	—	—	—
7	State[b]	0.88	0.33	0.03	−0.10	−0.14	0.05	0.10	−0.04	1.00	—	—	—	—	—
8	Size[c]	8.74	1.65	−0.05	0.18	0.02	−0.08	−0.11	0.14	0.17	1.00	—	—	—	—
9	Age	35.81	18.74	−0.10	−0.01	−0.22	0.03	−0.12	0.26**	0.38***	0.53***	1.00	—	—	—
10	Tran[b]	0.32	0.47	0.31**	0.14	−0.10	−0.11	−0.05	0.14	0.25*	0.17	0.12	1.00	—	—
11	Budget[c]	8.88	0.73	0.14	0.13	−0.11	−0.05	0.13	0.08	0.25*	0.26**	0.17	0.14	1.00	—
12	GDP[c]	11.20	0.67	−0.03	−0.07	0.09	−0.11	−0.02	−0.25*	0.20	−0.06	−0.14	−0.26*	0.05	1.00

Note. [a]$n = 57$; [b]dummy variable; [c]log-transformed, in 100 million RMB. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$ (two-tailed).

In this paper, the RESET test for model 2 is conducted. Moreover, the test results show that the F value is 1.711 ($p = 0.197$), with the significance being greater than 0.05. Therefore, it can be concluded that there is no missing item in model 2.

Third, a WHITE test [86] was performed to examine whether the sample met the homoscedasticity assumption of the OLS regression. When the significance of the F value in the WHITE test is smaller than 0.05, this indicates that heterogeneity exists in the data. In this situation, the heterorobust standard error needs to be calculated to reflect the significance of the regression coefficient [87]. The F value of model 2 in the WHITE test is 1.125 ($p = 0.490$), and its significance is greater than 0.05, which indicates that the data of model 2 are not heterogeneous. Similarly, a RESET test on model 4 was conducted in this paper. According to the test results, the F value is 1.121 ($p = 0.296$), with the significance greater than 0.05, indicating that there is no missing item in model 4. A WHITE test was then performed on model 4. The test results show that the F value of model 4 in the WHITE test is 2.021 ($p = 0.026$) with the significance smaller than 0.05, indicating that the data of model 4 are heterogeneous and that the heterorobust standard error must be calculated to reflect the significant factor of the regression coefficient (as shown in Table 4).

In this paper, the four models are constructed by the method of the hierarchical regression test, as shown in Table 4.

It can be seen from Table 4 that the F value of the model 2 is significant at the level of 10%. The adjusted R^2 is 0.138, obviously greater than the model 1, which indicates that the model's explanations for the dependent variable have been improved significantly after adding the independent variable. Among them, the Environmental perception ability is positively significant at the level of 5%; the Integrating and Coordinating Capability is positively significant at the level of 10%; and the p value of the Learning Capability regression result is greater than 0.1 and is not significant.

The F value of the model 4 is significant at the level of 5%, and the adjusted R^2 is 0.237 and increased greatly with the comparison of the model 3, which indicates that the model's explanations for the dependent variable have been improved significantly after adding the cross item. In the part of the cross item, the interaction between the Environmental perception ability and the Business Guanxi is positively significant at the level of 5%; the interaction between the Learning Capability and the Business Guanxi is negatively significant at the level of 5%; the interaction between the Environmental perception ability and the Political Guanxi is

Table 4: Hierarchical regression test.

Variables	Model 1	Model 2	Model 3	Model 4
Control variable				
State	−0.14	−0.16	−0.29	−0.26 (0.41) [0.35]
Size	−0.06	−0.04	−0.03	−0.02 (0.08) [0.09]
Age	−0.01	−0.01	−0.01	0.01 (0.01) [0.01]
Tran	0.58**	0.58**	0.64**	0.78*** (0.24) [0.26]
Budget	0.17	0.11	0.10	−0.01 (0.15) [0.16]
Gdp	0.05	0.13	0.13	0.19 (0.19) [0.17]
Independent variable				
Env	—	0.27**	0.24*	0.25* (0.14) [0.18]
Lea	—	−0.21	−0.22	−0.23 (0.15) [0.16]
Int	—	0.32*	0.32*	0.28 (0.19) [0.22]
Moderator				
Bus	—	—	0.17	0.21 (0.21) [0.21]
Pol	—	—	−0.11	−0.06 (0.11) [0.10]
Cross item				
Env ∗ Bus	—	—	—	0.42** (0.20) [0.22]
Lea ∗ Bus	—	—	—	−0.38** (0.17) [0.15]
Int ∗ Bus	—	—	—	0.18 (0.23) [0.19]
Env ∗ Pol	—	—	—	−0.26* (0.15) [0.16]
Lea ∗ Pol	—	—	—	0.02 (0.15) [0.14]
Int ∗ Pol	—	—	—	−0.21 (0.16) [0.16]
F value	1.31	1.20*	1.75*	2.02**
R^2	0.14	0.28	0.30	0.47
Adj. R^2	0.03	0.14	0.13	0.24

OLS standard errors are shown in parentheses. Heterorobust standard errors are shown in square brackets. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$ (two-tailed).

negatively significant at the level of 10%. In particular, the Business Guanxi positively adjusts the relationships with the Environmental perception ability and the Competitive Advantage; the Business Guanxi negatively adjusts the relationships with the Learning Capability and the Competitive Advantage; the Political Guanxi negatively adjusts the relationships with the Env and the Competitive Advantage, which means that H4a and H5a are verified, and an opposite conclusion has been drawn in H4b.

In Feng et al.'s [88] study on the Competitive Advantage, only the adjusted R^2 of the controlled variable's model is 0.007, and the R^2 of the model adding the independent variable is 0.097, far smaller than the results of this study. There are also many other studies in which the adjusted R^2 is comparatively small [14, 89]. Therefore, the explanations of the model 2 are acceptable. In Chung's [9] study on the moderating effect of the Chinese Guanxi, the adjusted R^2 of the model adding moderators and cross items is only 0.124, far smaller than the results of this study. Therefore, the explanations of the model 4 are acceptable.

5.2. Discussion

5.2.1. The Influence of the Dynamic Capability on the Competitive Advantage. According to the regression results, the positive effects of the Environmental perception ability on the Competitive Advantage of the project are under support, which means that the Environmental perception ability can significantly enhance the Competitive Advantage of the project. It is consistent with the current research results [13, 35, 36]. From a practical point of view, the biggest challenge that Chinese contractors face in undertaking overseas projects is the lack of full understanding and familiarity with the environment of the project host country or region. And the good Environmental perception ability can help those contractors anticipate all kinds of risks in advance.

In the circumstance that the actual environmental condition is unknown, contractors should plan to do the corresponding risk countermeasure and reduce the risk occurrence probability or reduce the loss as much as possible when it is unavoidable. The complexity of the project makes its construction risk higher. It is very important to estimate and prevent the unknown situation for the project progress and its smooth completion. It is more likely for a contractor who has a strong environmental perception ability to deal with the risk brought by the environmental change and thus enhance the competitive advantage of the project.

The influence of the Learning Capability on the Competitive Advantage is not significant, and H2 has not been verified. It contradicts with some existing research findings [17, 90], but there are also some scholars' researches which have not demonstrated the positive impact of the Learning Capability on the Competitive Advantage [91]. Crossan et al. [92] think that there is no direct relationship between the Learning Capability and the Competitive Advantage. Edmondson also suggests that there is no clear definition in how to gain the Competitive Advantage through the learning process [93]. The reasons why it is not significant can be analyzed from the following three aspects: firstly, the research proves that the materials holding the opinions that the Learning Capability has a positive correlation with the Competitive Advantage are mainly about the enterprises which make high demands on technical standards and innovation levels, such as new ventures or high-tech enterprises. But in the current situation, the most important thing for the current project is not the technology but the management and the construction progress and quality. Secondly, as Chinese contractors have undertaken overseas projects for only over 30 years, most projects contracted abroad are those of infrastructure, such as housing and transportation. The projects are mainly located in Asia and Africa, and most of them are still in the low-to-middle end. Besides, the international recognition of the Chinese contractors is still under the gradual enhancement, so high-tech standards are not required in the projects undertaken by the Chinese contractors. Thirdly, the Learning Capability of the international contractors is a potential ability of the future development, which can influence the long-term competitive advantages of contractors but has few effects on the performance of the current projects. Although the Learning Capability does not have a significant impact on the current project's competitive advantages, it is undeniable that the Learning Capability is very important for the sustainable development of the international contractors in the future as well as the transformation into high-end contracts.

The positive effect of the integrating and coordinating capability on the competitive advantage of the project receives much support, which means that the integrating and coordinating capability could enhance the competitive advantage of the project. This is consistent with existing research results [23]. When contractors undertake overseas orders, they have to quickly integrate resources at home and abroad to bid for constructions, which is a great challenge for their integrating and coordinating capability. The integration of their own and external available resources, and the adjustment of their staffing at the appropriate time, greatly impact the competitive advantage of the project. Regardless of the perception or predictions of the market environment, or the creative application of practice after absorbing new knowledge, only when putting the capabilities, resources, activities, information, and many other aspects into good integration and coordination, it will generate the highest value. Only through efficient execution will contractors be more likely to achieve project objectives.

5.2.2. The Moderating Effects of Chinese Guanxi on Dynamic Capacity and Competitive Advantage. The regression results demonstrate that business guanxi can strengthen the relations between contractor's environmental perception ability and project competitive advantage, which is consistent with the research results of Birkin et al. [94]. This study proves that a high degree of business guanxi is useful, conforming to preceding hypotheses in this research. As regards long-term development, with the introduction of business connections and resources through business guanxi, contractors will have easier access to the most cutting-edge information, fulfill owner's needs with better products and services, and win recognition of all sides in the industry; owners, supervisors, and suppliers will also prefer to further cooperate and communicate with contractors with good credit, and in turn, effective communication and cooperation will facilitate contractors to better achieve their project objectives.

To better illustrate the moderating effect of business guanxi on environmental perception and competitive advantage, this research takes advantage of a simple slope test to plot a moderating effect figure [95, 96]. The operation steps are as follows: set the values of business guanxi as low-level business guanxi (average value minus standard deviation) and high-level business guanxi (average value plus standard deviation), integrate the two values into the regression equation, draw the figure with a point plotting method, and then draw the moderating effect figure of business guanxi on environmental perception ability and competitive advantage, as shown in Figure 2.

The regression result suggests that political guanxi plays a negative role in regulating the relations between environmental perception ability and competitive advantage, which tallies with the initial hypothesis. Even if there has been no similar research result so far, certain studies have proven that political guanxi exerts a negative influence on dynamic capacity and competitive advantage [19, 97]. In accordance with unstable political situation, too close relations with the government may give rise to high risks. Since political guanxi often involves sensitive issues, the relations are highly likely to break off, and once the political situation changes, engineering orders attributed to preferential policies or led by the state also have to alter. Besides, market demand may conflict with government demand, in order to maintain political guanxi; even if contractors perceive the changes in the market environment, they have no other options but to choose between them, which may cause them to give up a part of interests and miss favorable opportunities for gaining market share and technology. In the meantime, the time and effort devoted to maintaining a high level of political guanxi are even more costly but less effective than those of competitors in obtaining resources and may even be counterproductive. Following the same operation principle, this research also plots the moderating effect figure of political guanxi on environmental perception ability and competitive advantage, as shown in Figure 3.

The regression result shows that business guanxi has a negative influence on learning ability and competitive advantage; that is to say, a high level of business guanxi makes contractors of outstanding learning ability less likely to achieve competitive project advantage. Although the relevant literature has not verified this conclusion, one possible explanation for this unpredictable result is that contractors of outstanding learning ability make substantial investments in knowledge acquisition, information exchange, and the innovative application of technology and services. As for information gained through a business relations network, for the sake of the long-term development of enterprises, contractors may attach more importance to

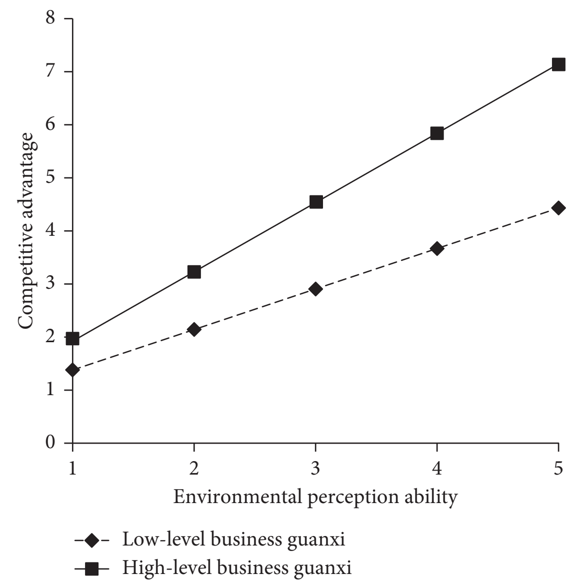

Figure 2: The interaction of environmental perception ability and business guanxi.

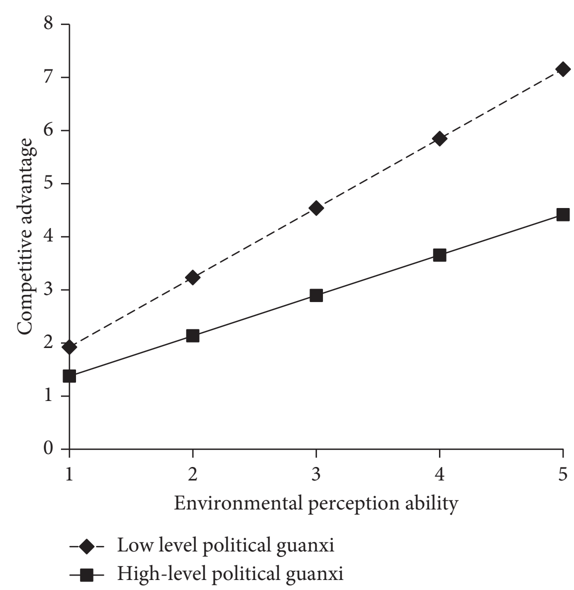

Figure 3: The interaction of environmental perception ability and political guanxi.

technology, products, and services newly emerging (or potentially of higher value in the future) so that they can take a leading position as early as possible. The innovation cost is extremely high and faces considerable uncertainties and risks. Once the market environment changes, the previous investment may come to naught, become lost expense, and result in a waste of resources. However, the resources an enterprise owns are limited. If too many resources are invested in a particular aspect, other aspects are bound to be severely affected. In other words, when too much energy is expended on technological products which can generate future value, input into projects under construction or in operation will be correspondingly lessened, which may hinder competitive advantage being obtained from current projects.

Additionally, due to the reciprocal nature of relations [98], contractors are under an obligation to afford their business partners some knowledge and information [49] so that business partners may learn from successful experience, mature, and create useful technological products by imitation. Relations enable the partners to obtain knowledge of high value at a lower cost and, therefore, reinforce their strength. Where providing the same technical service, contractors pay a higher cost, and the project profitability will naturally decline as the contract amount is constant. Similarly, this research demonstrates the moderating effect figure of business guanxi on learning ability and competitive advantage, as shown in Figure 4.

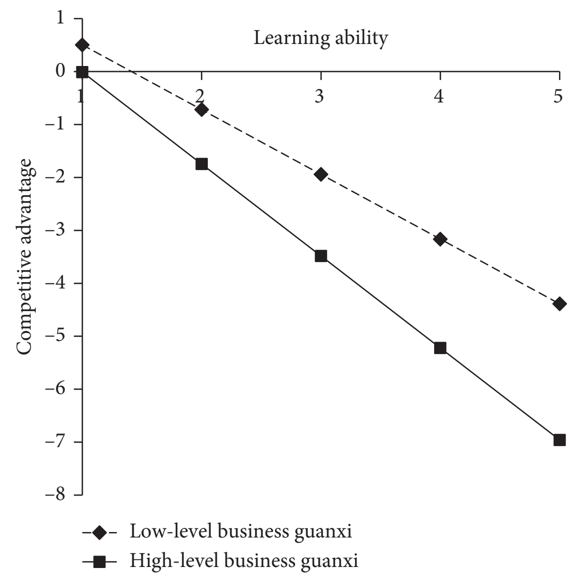

Figure 4: The interaction of learning ability and business guanxi.

6. Conclusion

This study primarily aimed to research the impact of dynamic capacity of Chinese international contractors on project competitive advantage and the moderating effects of Chinese guanxi. The findings suggest that the environmental perception capability and the integration and coordination capability of the dynamic capability have a significant positive effect on the project competitive advantage; business guanxi positively moderates the relationship between the environmental perception capability and the competitive advantage. Business guanxi also negatively moderates the relationship between learning ability and competitive advantage, while political guanxi negatively moderates the relationship between the environmental perception capability and competitive advantage.

The key contributions of this research are twofold. First, it makes a theoretical contribution by offering a new, integrative position of the relationship between dynamic capabilities, guanxi, and competitive advantage. This paper contributes to the construction management literature not only by providing empirical evidence on the dynamic capability and competitive advantage of Chinese international contractors but also by expanding guanxi research. Specifically, this research intends to reveal whether the environmental perception ability, learning ability, and integration and coordination capability of Chinese international contractors create a prominent impact on competitive advantage and whether business guanxi and political guanxi can dramatically regulate relations between them. This study complements existing research on dynamic capacity and competitive advantage [43, 99]. Previous research was mostly founded on manufacturing or high-tech enterprises, and very few considered contractors. Therefore, this study examined the applicability of research theories concerning Chinese international contractors exploring the overseas market, which shows that dynamic capacity theory is also applicable to Chinese international contractors. Furthermore, excluding learning ability, this study verified that environmental perception ability and integration and coordination capability exercise a positive influence on competitive advantage. Second, this study improves research on Chinese guanxi empirically and expands research on Chinese guanxi in the international engineering field [100, 101]. The results may also help Chinese contractors by providing strategic reform guidance and sustainable development in international construction projects.

Some limitations of this study require future research. First, considering a lack of measurement of project competitive advantage in the existing literature, the discoveries this study build upon need to develop more indicators to more comprehensively measure the results. Despite this limitation, this study corresponds with previous findings on the impact of dynamic capacity and competitive advantage [12].

Second, even though much effort was devoted in this study to increasing the sample size of questionnaires, offering detailed explanations, and ensuring the proportion of valid questionnaires, the sample size is still very modest. In comparison with other studies on Chinese guanxi, for example, Park and Luo's study [43] with a sample size of 128 and Chung's [9] with 96, this study merely has 57, which is modest because a larger sample size can lessen possible deviations and increase the reliability and general adaptability of results [49, 76]. The conclusions of this research require reconfirmation before being widely applied. These issues will be addressed in the authors' future research.

Data Availability

The authors worked with reputable contractors on a funded research project. In the agreement of their collaboration, any kinds of data are owned by the company and thus are confidential to anybody else. The authors thank the readers for understanding their collaboration agreement.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Impact of Attitudinal Ambivalence on Safety Behaviour in Construction

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Unsafe acts have been identified as a major factor of construction accidents. The Theory of Planned Behaviour (TPB) has been used to explain the factors influencing unsafe behaviour, by establishing the relationship between attitude, intention, and behaviour. However, the existing research on the relationship between safety attitude and safety behaviour could not fully explain the decision-making process of unsafe acts, in that the relationship could be mediated by attitudinal ambivalence, which is caused by conflicting information sources and the social network pressure of peer workers. This research examined whether attitudinal ambivalence was a mediating factor, either fully or partially, in the relationship between safety attitude and safety behaviour by expanding the TPB model. Data were collected from questionnaire survey of 228 construction workers. The results showed that attitudinal ambivalence existed as a partial mediating factor in the relationship between safety attitude and safety behaviour. This paper contributed to the body of knowledge on safety management by recognizing the role of attitudinal ambivalence in construction workers and integrated it into the TPB model. This research will be helpful in providing greater understanding of the dynamic and complex decision-making process of unsafe behaviour given multiple information sources and conflicting environments.

1. Introduction

Construction is one of the most important industries worldwide as it provides up to 10% employment and economic growth. However, construction has also been classified as one of the most hazardous industries across the world [1–3]. Safety accidents cause fatalities, injuries, financial losses, and schedule overruns, and it may even impact construction workers' family life and welfare due to the spillover effect of the safety climate at work [4]. It is well accepted that a decrease in the number of workers' unsafe acts can improve the safety performance of construction projects, and substantial research efforts have been undertaken aiming to eliminate unsafe acts. One stream of efforts addresses workers "not knowing" work-associated risks and aims to improve safety training [5] and teach them what to do to accomplish their job safety. Another stream of research addresses workers "not willing to perform safely" [6], which could be caused by a series of factors at the individual, group, and organizational levels [7]. Individually, "not willing to perform safely" can be considered as a decision-making process [8] and can be explained with psychological theories because they address how the mind, perceptions, and beliefs influence safety behaviour. The prevailing theoretical framework of unsafe acts is the Theory of Planned Behaviour (TPB) [9], and it has been widely applied to analyse unsafe acts in construction [10, 11] and other research fields.

However, a series of theoretical and empirical studies [12] showed that various factors at the organizational and individual levels play important roles in the decision-making process and those factors can be conflicting. The Theory of Planned Behaviour does not harbour the attitudinal ambivalence that is caused by conflicting factors leading to unsafe acts and therefore provides an incomplete picture of the possible relationship between safety attitude and safety behaviour. The research into contradictory factors with positive and negative effects and their influence on safety behaviour is still in its infancy.

The ambivalence comes from the conflicts in cognitive and affective attitudes. In construction safety, conflicts may happen in several ways. First, the priority of safety could be conflicting with an emphasis on schedule or cost. Second, construction workers may change their safety acts when they choose to enjoy the convenience or are under stress, anger, and difficult operating conditions [13]. Third, safety trainings can be conflicting with habitual unsafe behaviour in construction groups, which may lead to unsafe behavioural intent when the habitual unsafe behaviour prevails. Fourth, safety attitudes and safety behaviour can be inconsistent among different team members, and the influence from their coworkers can be greater than that from the project organization's higher safety management, which makes it harder for safety leadership to be effective in construction crews.

The abovementioned bipolar continuum of safety attitude could be described with attitudinal ambivalence. Attitudinal ambivalence was identified in social psychology in the 1990s, and it was referred to the coexistence of positive and negative cognitive appraisal and affective experience towards certain objects [14]. Recently, it has been used in the research of safety attitude and unsafe behaviour [15]. Under multiple information sources and a variety of psychological effects, unsafe acts of construction workers can be propagated, accumulated, and repetitive [16].

In this research, we examined the ambivalence of their attitude towards unsafe acts that may be influenced by their cognitions of safety risks, their communications with their peer workers and foremen, and the organizational priorities over safety. The conflicting information sources and the social network pressure of peer workers caused ambivalent attitude over safety acts and influenced the relationship between their safety attitude and behaviour. Establishing the effect of attitudinal ambivalence on unsafe behaviour will be helpful to understand the dynamic and complex decision-making process of unsafe behaviour.

In the next sections, the concept of attitudinal ambivalence and the identified group influence on construction workers' unsafe acts will be discussed, and the possible role of attitudinal ambivalence will be hypothesized for model fitting and comparison. Then, the questionnaire of construction workers' usage of personal protective equipment will be introduced. The results will be examined, and the model will be fitted to decide whether attitudinal ambivalence is one of the factors leading to unsafe acts. In the end, a discussion and concluding remarks will be provided to help construction managers control unsafe behaviour by the control of attitudinal ambivalence.

2. Theoretical Background and Research Hypothesis

2.1. TPB and Construction Safety Research. Ajzen developed the Theory of Planned Behaviour (TPB) and identified factors of human behaviour, which included attitude, subjective norm, and perceived behavioural control [17]. Attitude refers to the value attributed to the performance of the behaviour, and the most favourable behaviour is more likely to happen. The subjective norm indicates social pressure to perform certain behaviour; the behaviour under greater pressure is more likely to happen. The perceived behavioural control refers to a prejudgement of the possibility of performing certain behaviours; the easier behaviour is more likely to happen. The intention is an indication of a person's readiness to perform a given behaviour, and it is considered to be the immediate antecedent of behaviour. The TPB considers individual and environmental influence and could be used to explain human behaviour in a satisfactory extend. A search of existing literature showed that TPB has been cited more than 10,000 times and successfully applied in various research fields to predict safety-related behaviour such as unsafe driving behaviour [18], green exercise [19], and the relationship between safety climate and unsafe behaviour [10, 11].

To promote safe behaviour on construction sites, previous researchers measured safety attitude [24], analysed the relationship between safety attitude and safety performance [25], and discussed how safety interventions could improve safety attitude and performance [26]. Mohamed et al. found that workers' attitudes towards safety responsibilities and their risk perceptions explained their intentional behaviour [27]. Some of the research had identified that safety attitude could be under conflicting influencing factors and it is possible to impact the relationship between attitude and behaviour. In this research, by applying theoretical model fitting, the causal effect of attitude on behaviour can be further explored and discussed.

In construction safety, Cavazza and Serpe used TPB to argue that the improvement of safety performance was caused by psychological changes and positive attitudes after safety training programmes [15]. Fang developed a framework of social psychological causes of unsafe behaviour based on the TPB and used it to discuss the relationship between safety attitude and unsafe behaviour [8]. Goh and Binte Sa'adon used TPB to identify the key variable of the cognitive decision-making process of unsafe behaviour of scaffolders [20].

Applications of TPB model often expanded it with extra factors to better explain unsafe behaviour, as TPB was an open theoretical framework and new factors could be added to improve the explanation of human behaviour. The descriptive norms were distinguished from injunctive norms to better predict intentions and behaviour [21]. Other factors were added to TPB model as the leading factors of attitude and subjective norms, which included past behaviour and habits, belief salience, morality, and self-identity [22], and moral norms, which included self-identity and group identity [23]. In this research, a focus was placed on the attitude factor; particularly, this research expanded the construct of attitude and introduced the concept of ambivalent attitude.

2.2. Attitudinal Ambivalence. Various factors may lead to conflicting information and stimuli regarding construction workers' safety attitude [28], and those factors may come from the individual level, the group level, and the organizational level. For example, Wu et al. identified management safety commitment, team safety climate, and personal safety responsibility as factors of safety attitudes [29]. Safety training not only increases safety knowledge but also improves safety climate on site and could be a positive factor of construction workers' safety attitude. On the other hand, acting in a safe way may sacrifice comfort and convenience. For example, dumper drivers may not get off the truck every time during unloading because they tried to save some efforts [30]; workers may also refuse to wear helmets because it is too hot in the summer. These conflicting factors may lead to the unstable, incongruent, and ambivalent safety attitude in construction crews. In addition, attitudes towards safety in the construction industry were affected by past experience; victims of accidents tended to be more careful while nonvictims felt confident about their own behaviour [31].

Construction crew members are under great peer pressure from their groups to behave unsafely if unsafe behaviour prevails, and construction managers' commitment to safety could be conflicting with the unsafe behaviour of the construction coworkers. Zohar and Tenne-Gazit stated that interaction and leadership were the predictive factors of the emergence of organizational climate [32], and safety culture emerged from the interactions and influence of multiple organizations [33]. In small and medium construction groups, frank and frequent safety communication between construction workers and managers could improve safety performance [34]. Friendship network in the construction crews can compensate poor safety climate [35], and social pressure in crews can influence the strength of safety climate [11]. Novice and younger construction workers relied on the communications with their peers to attain safety knowledge [36]. The safety performance of migrant or ethnic minority workers being worse than that of local workers could also result in the negative safety attitudes as a group [37].

Therefore, it is necessary to study the existence and measurement of contradictory attitude towards safety behaviour, and attitudinal ambivalence may provide an explanation of the cognitive decision-making process with individual's intent of unsafe acts. Attitudinal ambivalence describes the coexistence of positive and negative attitude elements. Ambivalent attitude comes from conflicts among cognitive and affective dimensions of attitude, either within these dimensions or between them [38]. Intracomponent ambivalence stands for the coexistence of positive and negative cognitions or feelings against certain attitude objects. For example, believing PPE an effective protection from danger but useless in safe environment is ambivalence within the cognitive attitude, while feeling protected by personal protective equipment and feeling tedious wearing them are ambivalence within the affective attitude. Intercomponent ambivalence stands for the coexistence of positive cognition and negative feelings or that of negative cognitions and positive feelings towards attitude objects. For example, knowing to wear safety helmets and feeling uncomfortable wearing them represent ambivalence between cognitive and affective attitudes.

The measurement of attitudinal ambivalence could be direct or indirect. Respondents could be asked directly if they have conflicting beliefs and feelings towards unsafe acts [39], or they could be asked to rate the extent of their positive and negative beliefs and feelings separately, and the response would be calculated to indicate ambivalence [40].

Psychological studies have verified that conflicts could weaken behavioural intentions or the relationship between attitudes and behaviour [41]. Cavazza and Serpe found that attitudinal ambivalence can mediate the impact of safety climate on complying with the safety behaviour rules [15]. However, safety climate is a collective phenomenon, and individually, safety behaviour is influenced by safety attitude. This research concerns the cognitive decision-making process of safety behaviour by studying the ambivalent safety attitude. As such, the aim of this research was to examine how the ambivalent attitude takes effect in the relationships between safety attitude and safety behaviour by using TPB.

2.3. Research Hypothesis. According to the Theory of Planned Behaviour [9], safety attitude, subjective norms, and perceived behavioural control all have a positive correlation with safety intent, which is closely related to safety behaviour. Therefore, this research established Hypothesis 1 as follows: safety attitude, subjective norms, and perceived behavioural control have a positive correlation with safety intent.

Given the above discussion, attitudinal ambivalence has an impact on the relationship between safety attitude and safety behaviour. However, the path of the impact was still unclear. Existing literature argued that attitudinal ambivalence made behavioural decisions harder to make [42], as well as decreased the consistency of attitude and the confidence of certain behaviour [43] because the ambivalence undermined the persistence, resistance, and information process of attitude.

In line with the abovementioned literature on attitudinal ambivalence, this research proposed the hypothesis that attitudinal ambivalence had a mediating impact, at least in part, on the relationship of safety attitude and safety intention. The fully mediating impact means that the direct path from the independent variable to the indicator is zero, while the partially mediating impact means that the direct path from the independent variable to the indicator is decreased by the mediator. Therefore, this research compared the fully and partial mediating models to examine the impact path of attitudinal ambivalence, as shown in Figure 1. The fully mediating model suggests that safety attitude does not directly influence safety behaviour intent without the impact of attitudinal ambivalence, while the partial mediating model suggests that attitudinal ambivalence weakens the impact of safety attitude on safety behaviour intention. Attitude influenced behavioural intention immediately, and behaviour is highly related to intention. On the other hand, behaviour with objective but questionnaire could be subjective and not a best way to gather behaviour data. Therefore, this research did not include behaviour data in the model and the questionnaire. Correspondingly, the hypothesis is as follows:

> H1: Safety attitude, subjective norms, and perceived behavioural control have a positive correlation with safety intent.

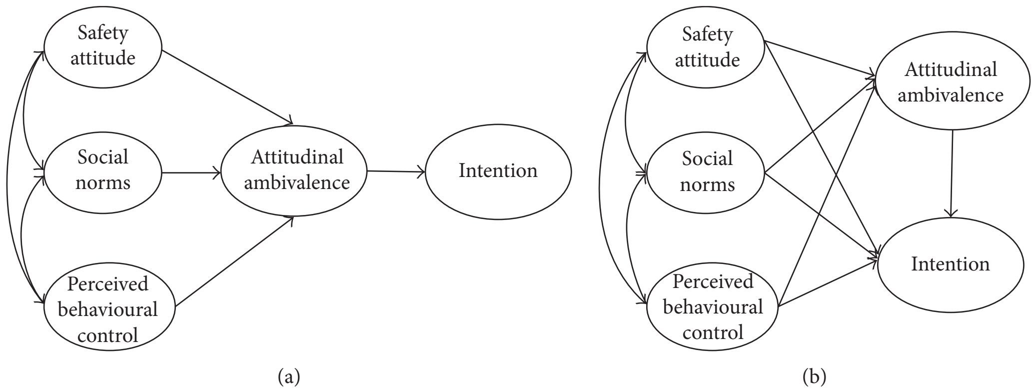

Figure 1: Fully mediating model (a) and partial mediating model (b).

H2a: Attitudinal ambivalence fully mediates the correlation of safety attitude, subjective norms, and perceived behavioural control with safety intent.

H2b: Attitudinal ambivalence partially mediates the correlation of safety attitude, subjective norms, and perceived behavioural control with safety intent.

3. Survey Questionnaire Development

The failure to correctly wear personal protective equipment (PPE) was chosen as the behaviour of discussion instead of general "unsafe acts" because PPE could help workers avoid injuries when falling from heights and struck by objects, which combined could account for more than 70% of all accidents in construction in the US and more than 60% in China. Thus, the use of PPE was an essential act of safety that could greatly reduce the number of injuries.

3.1. Measurement of Safety Attitude. Existing literature has developed statements to measure safety attitudes; these statements were adapted to PPE usage. The measurement of safety attitude contained items to assess cognitive and affective attitudes towards safety behaviour and risk perceptions [44]; safety values and internal tendencies [45]; with the focus on the workers' perception of PPE and their risk assessment. In this research, the statements were adapted from Braham [46] including whether workers were aware of the circumstances for using PPE, the benefits of using it, and the risks of not using it. Nine statements were developed for safety attitudes.

3.2. Measurement of Attitudinal Ambivalence. For the attitudinal ambivalence component, questions included direct emotions towards PPE, satisfaction with PPE usage, and past experience. The way we adapted to develop the attitudinal ambivalence statements was to select positive and negative statements of feelings towards safety behaviour from various sources [39, 46] and to gather seven descriptive words to describe the feelings, as well as another two questions about their past experience gaining benefits from using PPE and their overall satisfaction of the PPE management on site.

3.3. Subjective Norms and Perceived Behavioural Control. The measurement for subjective norms, perceived behavioural control, intention, and behaviour was also developed. Subjective norms were the perceived beliefs regarding the social norms of group behaviour; thus, the statements represented "what other people would do" and "what other people might think." The influence of interpersonal relationship on their behaviour was also measured through statements including "good relationships with my coworkers help me wear PPE correctly" [47]. The subjective norms usually came from supervisors, coworkers, and family, so four statements were developed for subjective norms. For perceived behavioural control, six statements were used to measure how much control they believe they have on using PPE based on Ajzen [9] to discover the perceived behavioural control under normal and abnormal situations, as well as conditions perceived as necessary. The intention was measured with the frequency of using PPE in the future.

3.4. Choosing Appropriate Items for the Instrument. A total of 50 statements were developed in the survey questionnaire, and they were revised by an expert focus group consisting of five engineers, who were in charge of project safety and quality and had more than five years of experience, and five academics in construction safety. The focus group session first checked for double-barrelled questions, and six statements were identified as redundant and deleted. Second, every statement was worded to be plain, simple, clear, and direct in language to ensure clarity and ease of comprehension. Third, the focus group reviewed the questionnaire, and participants in the group provided their experience with the PPE issue on site, deleted another four statements that did not represent the workers' experience and concerned on using PPE, and rephrased five statements to better describe their experience.

Overall, 31 statements were ultimately chosen for the questionnaire, which were also called "items" in this research. They consisted of eight items for safety attitude, items SA1 to SA8; eight items for attitudinal ambivalence, items AA1 to AA8; five items for subjective norms, items SN1 to SN5; seven items for perceived behavioural control, item PBC1 to PBC7; and 3 items for intentions, items INT1 to INT3. All questions asked workers to express the level of agreement (or disagreement) on a five-point Likert-type scale, but answers for each question varied according to their particular statement. In addition, the questionnaire also included five demographic questions about respondents' age, gender, trade, education and training, and number of years working in the construction industry.

4. Data Collection and Analysis

4.1. Data Collection. The survey questionnaire in Chinese was distributed to 290 workers in ten construction sites in Dongguan, Guangdong Province, and Wuhan, Hubei Province, in China, including five commercial construction sites and five metro construction sites. The commercial construction sites were chosen randomly from all government-invested projects in Dongguan, and the metro sites were also chosen randomly from all metro construction sites in Wuhan. The project managers and site foremen helped with the onsite distributions of the anonymous survey questionnaire, but they were not aware of the content of the questionnaire. All instructions were given by the researchers directly to the workers, so that the responses were trustworthy and under no manipulation. Workers were asked to gather in a large room on site after lunch, so that completion of the questionnaire would not interrupt their work. The researchers explained that the survey was purely for scientific research and the confidentiality would be guaranteed and that the data from the questionnaire were anonymous and collected directly by the researchers. The questionnaire survey took 20 minutes at each site.

In total, 278 sets of questionnaires were collected. Data preprocessing showed that 27 respondents did not answer all the questions. Another 23 respondents had answers that were identical to those of others and therefore might not be willing to answer the questionnaire seriously and copied their coworkers' responses. Their responses were no longer suitable for further analysis. As a result, data preprocessing excluded 27 incomplete sets of data and 23 sets of duplicate data. As a result, 228 sets of data (78.6% responses rate) were valid and analysed with SPSS.

4.2. Data Analysis. In the 228 valid responses, 198 of the respondents were male and 30 were female. They covered a variety of trades, including bar benders, concrete workers, scaffolding workers, electricians, labourers, carpenters, masons, and drivers. Only five respondents had received high school education, and 72% of the respondents were 20 to 39 years old. A total of 37.5% of them had worked in the construction industry for less than three years, and approximately 10% of them had worked in the industry for more than eight years.

The intraconstruct reliabilities were examined with Cronbach's alpha as shown in Table 1. Cronbach's alpha must be larger than 0.7 to indicate good reliability. Cronbach's alpha values for all constructs were above 0.7, suggesting strong internal consistency of all measures. Therefore, the reliability of the questionnaire was verified. Table 2 also shows the result of the corrected item-total

Table 1: Confirmatory factor analysis.

Items		Factors	Standard estimates	p
SA7	<---	Safety attitude factor	0.622	—
SA6	<---		0.802	***
SA5	<---		0.829	***
SA4	<---		0.868	***
SA3	<---		0.843	***
SA2	<---		0.868	***
SA1	<---		0.856	***
AA8	<---	Attitudinal ambivalence factor	0.666	***
AA5	<---		0.836	***
AA4	<---		0.844	***
AA3	<---		0.880	***
AA2	<---		0.771	***
AA1	<---		0.749	***
PBC6	<---	Perceived behavioural control factor	0.716	***
PBC5	<---		0.715	***
PBC3	<---		0.855	***
PBC2	<---		0.812	***
PBC1	<---		0.664	***
PBC7	<---		0.582	***
SN1	<---	Subjective norm factor	0.914	***
SN2	<---		0.949	***
SN3	<---		0.874	***
SN4	<---		0.796	***
SN5	<---		0.834	***

Note. ***Significance level is $p < 0.001$, **significance level is $p < 0.01$, and *significance level is $p < 0.05$.

Table 2: Correlation and credibility test.

Factors	Items	Correlation
Safety attitude factor Cronbach's alpha = 0.945	SA1	0.822
	SA2	0.835
	SA3	0.822
	SA4	0.837
	SA5	0.805
	SA6	0.779
	SA7	0.811
	SA8	0.354
Attitudinal ambivalence factor Cronbach's alpha = 0.816	AA1	0.604
	AA2	0.702
	AA3	0.814
	AA4	0.751
	AA5	0.776
	AA6	0.449
	AA7	−0.293
	AA8	0.677
Perceived behavioural control factor Cronbach's alpha = 0.742	PBC1	0.538
	PBC2	0.714
	PBC3	0.698
	PBC4	−0.081
	PBC5	0.646
	PBC6	0.607
	PBC7	0.568
Subjective norm factor Cronbach's alpha = 0.797	SN1	0.556
	SN2	0.791
	SN3	0.766
	SN4	0.583
	SN5	0.568

correlation analysis, which was to make sure that every item was correlated with other statements within the same construct. The value should be larger than 0.5 to suggest a good correlation within constructs. Items SA8, AA6, AA7, and PBC4 were deleted for their low interconstruct correlation scores, which suggested poor correlation with other statements and those statements was not measuring the same construct [48]. When deleted, Cronbach's alpha value would be above 0.5, and the reliability would be significantly increased. Close examination of these deleted statements revealed that SA8 could be too vague for respondents to answer and should be excluded from the safety attitude factor; AA6 was about a general feeling of working safety, and AA7 was about an attitude to learn the use of PPE, and these two should not have been used to measure attitudinal ambivalence; and PBC4 was more likely an evaluation of behavioural intent.

Next, confirmatory factor analysis was conducted with AMOS 18.0. Each construct was examined to check whether the measurement was unidimensional. Fitness was assessed by chi-square and χ^2/df value, Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), and root mean square error of approximation (RMSEA). Good fit of model should follow the criteria of χ^2/df less than 3, CFI and TLI greater than 0.90, and RMSEA less than 0.08. Confirmatory factor analysis also indicated the convergent validity. The standardized factor loading should be at least 0.5 and ideally 0.7. The analysis showed that the factor loading for most statements was above 0.7, except SA7 was not significantly related to safety attitude, which was unacceptable. In order to obtain good model fit and achieve validity, SA7 was deleted. Furthermore, the factor loading for AA8 and PBC7 was 0.582 and 0.666, and they were also excluded for the model fitting. The final results are shown in Table 1 and note that symbol "<---" means the items in the first column are the constituents of the constructs in the second column.

5. Results and Discussion

5.1. Results. Structural equation modelling (SEM) was used to fit the TPB model and reveal the correlation among components. SEM can be considered as a series of tools for data analysis to test theoretically derived and priori specified causal hypotheses (Mueller and Hancock, 2008). In SEM, variables are distinguished as latent variables and measured variables. The traditional and typical SEM applications can be divided into the following three categories: a measured variable path analysis, which explores the hypothesized causal relations among measured variables; a confirmatory factor analysis, which explores the causal relations between latent variables and measured variables; and the latent variable path analysis, which explores the causal relations among latent constructs.

At first, the fully mediating TPB framework in Figure 1 was fitted, as shown in Table 3, where the column "standard estimates" indicates the estimated regression weight, the column "standard error" indicates the standard error of regression weights, the column "critical ratio" indicates the critical ratio as dividing the regression weight estimate by the estimate of its standard error and corresponds to the last column indicating p-value. A p value of 0.05, which is considered significant, requires a critical ratio of 2.07. The criteria used in confirmatory factor analysis were also applied here to determine whether the model was a good fit. The results show that the fully mediating model was not a good fit, since CFI was 0.894, and it had to be more than 0.9 to be a good fit. The RMSEA was 0.094, and it had to be less than 0.08 to be a good fit. Note that the symbol "<---" means that the constructs on the right of the sign were factors influencing the constructs on the left.

Then, the partial mediating model was examined, and it turned out to be a good fit ($\chi^2/df = 2.338$, CFI = 0.934, TLI = 0.913, RMSEA = 0.077), as shown in Table 4 and Figure 2. In Figure 2, rectangles represent observed variables or questionnaire statements; small circles on the left side represent the residue; big circles represent latent factors, including model constructs; and arrows represent path directions and coefficient estimates, and the path significance is shown on each arrow. The single directional arrows denote the definite relationship between the related constructs, while the double directional arrows denote the covariances among constructs and those relationships were not included in the model or the hypothesis, and thus, no significance value was shown on these bidirectional arrows. A path was considered significant if the significant level of the path was under 0.05. In this model, the predictors of behaviour explained 82.0% of its variance, and the predictors of intention explained 88.1% of its variance. Note that the symbol "<---" means the constructs on the right of the sign were factors influencing the constructs on the left.

Overall, the parameter fits and estimates supported H1 and H2b, the partial mediating role of attitudinal ambivalence in the relationship between safety attitude and behavioural intention in Section 2.3. The expanded TPB model was suitable for modelling the partial mediating role of attitudinal ambivalence in the safety attitude and safety intention relationship. The moderate model confirmed factors of intentions and suggested that ambivalent attitude was an important factor of unsafe behaviour intention.

5.2. Discussion. This research investigated the influencing factors and paths of construction workers' intentions to behave unsafely. The questionnaire survey results supported the expanded TPB model with attitudinal ambivalence as a partial mediating factor of unsafe intentions. The results also corresponded with those of psychological research on health risk-related behaviour, including the finding that changes in attitudes were caused by strengthened recognition of target behaviour and that social norms and perceived behavioural control both have substantial influence on intentions.

The results suggested that the change in unsafe behaviour intentions was greatly impacted by ambivalent attitude and perceived behavioural control. However, the link between safety attitude and behaviour intentions was weak. One of the explanations could be that because the ambivalent attitude was considered in the model, it took place of the safety attitude. When construction workers had an ambivalent attitude towards safety acts during their decision-making process, they hesitated and may not have taken actions following their cognition and perception on

Table 3: Fitting results of fully mediating model.

			Standard estimates	Standard error	Critical ratio	p
Intention	<---	Attitudinal ambivalence	0.709	0.149	4.756	**
Attitudinal ambivalence	<---	Perceived behavioural control	0.997	0.099	10.401	***
Attitudinal ambivalence	<---	Safety attitude	0.065	0.057	1.015	0.310
Attitudinal ambivalence	<---	Subjective norms	0.009	0.034	0.192	0.848

χ^2 (203) = 608.214, χ^2/df = 2.996, CFI = 0.894, RMSEA = 0.094. *Note*. ***Significance level is $p < 0.001$, **significance level is $p < 0.01$, and *significance level is $p < 0.05$.

Table 4: Fitting results of partial mediating model.

			Standard estimates	Standard error	Critical ratio	p
Intention	<---	Attitudinal ambivalence	0.813	0.230	4.116	***
Attitudinal ambivalence	<---	Perceived behavioural control	0.261	0.367	0.955	0.340
Attitudinal ambivalence	<---	Safety attitude	0.850	0.459	2.910	*
Attitudinal ambivalence	<---	Subjective norms	0.155	0.060	3.224	**
Intention	<---	Perceived behavioural control	0.730	0.291	3.483	***
Intention	<---	Subjective norms	0.453	0.137	3.316	***
Intention	<---	Safety attitude	0.090	0.107	1.087	*

χ^2(234) = 546.996, χ^2/df = 2.338, CFI = 0.934, RMSEA = 0.077. *Note*. ***Significance level is $p < 0.001$, **significance level is $p < 0.01$, and *significance level is $p < 0.05$.

the safety acts. Therefore, the direct effect of safety attitude on behaviour intention was weakened.

Conflicts in construction workers' beliefs and feelings generate attitudinal ambivalence, and it may eventually temper their decisions to act safely. To control the ambivalence, managerial strategies should be implemented including decrease of ambivalence in the cognitive attitude, the affective attitude, and the interaction between them. Specifically, safety managers should be consistent to the "safety first" principle, instead of compromising safety under schedule or cost pressures, and avoid the ambivalence caused by conflicts of cognitive attitude. While they continually organize safety trainings, they should also pay special attention to workers' negative feelings and avoid the ambivalence caused by the conflicts of cognitive and affective attitudes. It is also important for the managers to eliminate habitual unsafe behaviour and resistance on safety rules and regulations and develop a positive habit of following safety rules. If managers encourage a caring environment to make workers believe their coworkers will expect them to follow safety rules, the safety performance may improve. However, managers may take advantage of attitudinal ambivalence when they try to eliminate habitual unsafe behaviour by introducing intensive safety training and intervention to arouse the ambivalence first and then changing construction workers' unsafe attitude by controlling the ambivalence.

Besides attitudinal ambivalence, construction workers' groups had an impact on attitudinal ambivalence and behaviour intentions through the factor of social norms because social influence is one of the factors in personal decisions. It has been traditionally observed that the pressure from workmates of certain social norms influenced workers' behaviour [49]. In construction safety research, Yagil and Luria suggested high-quality friendship compensated for inequity of safety climate and improved workers' safety attitude and behaviour [35]. This research revealed the influence of social norm to intentions. Future research may be focused on exploring the mechanism of the influence of social norms, and the organizational strategies to improve safety attitude in construction groups of migrant workers with high mobility.

One of the limitations of the proposed TPB model was that it did not include the behaviour component. By collecting real data of construction workers' unsafe behaviour with information technology, it is possible to verify whether the proposed TPB model could predict unsafe behaviour effectively. Findings of this research explained the conflicts in construction workers' safety decision-making process with the partial mediating factor of attitudinal ambivalence and enriched the research on safety management with psychological theories and methods. Future work is also concentrated on the factors leading to attitudinal ambivalence and their interactive dynamics to influence the attitudinal ambivalence and eventually the safety behaviour.

6. Conclusions

This research discussed the attitudinal ambivalence that influenced the intentions of behaviour and identified the impact path of attitudinal ambivalence on behavioural intention and safety behaviour. The results obtained from the questionnaire survey on 228 construction workers showed that safety recognition, social norms, and perceived behavioural control had significant influence on intentions of unsafe acts. The results from structure equation modelling (SEM) analysis explained 82.0% of its variance. Model fitting showed that attitudinal ambivalence had a partial mediating impact on unsafe behavioural intentions, while attitudinal ambivalence and subjective norms were the strongest predictors of intention.

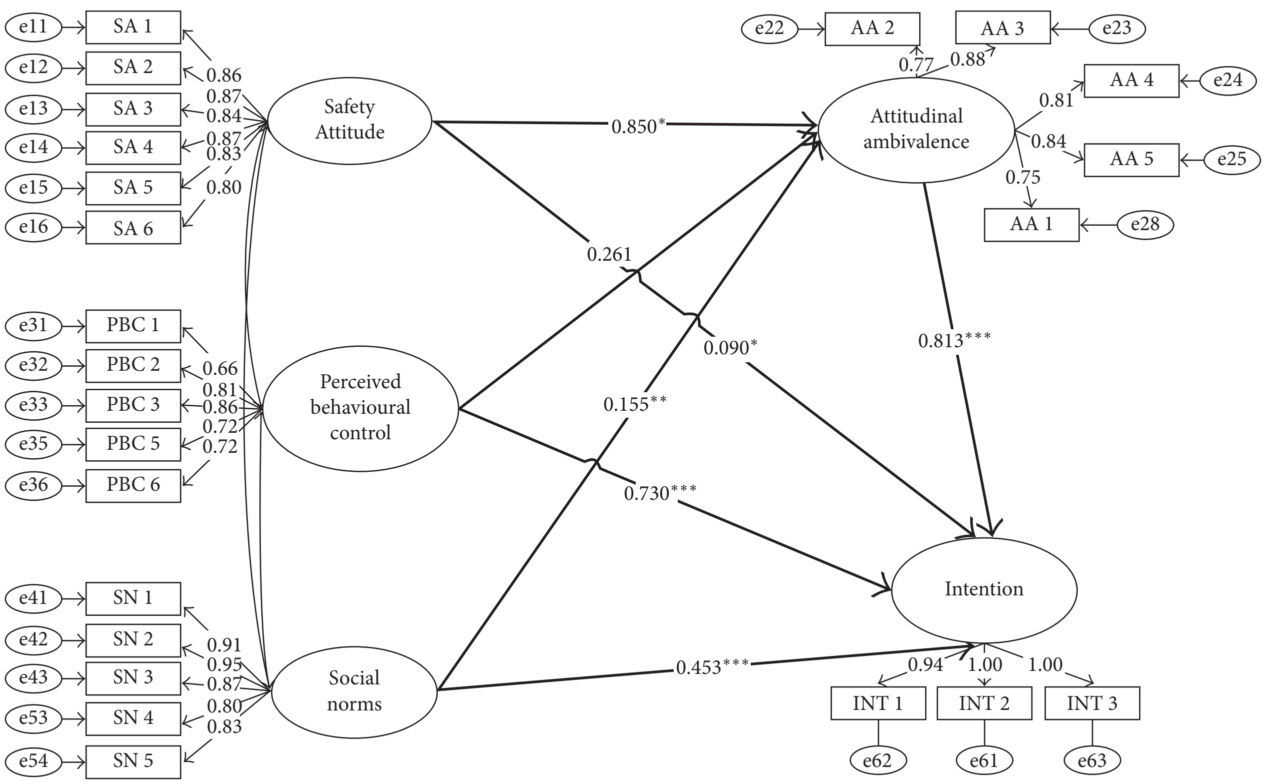

Figure 2: Fitting of the partial mediating model (2-column fitting image). *Note.* ***Significance level is $p < 0.001$, **significance level is $p < 0.01$, and *significance level is $p < 0.05$.

This study applied psychological theories to develop an understanding of the leading factors leading to safety behaviour in construction. Anchoring at the psychological perspective is an innovative and developing point of view in construction safety research. In expanding this line of research to other safety violations, researchers and practitioners may design more effective and human-oriented safety interventions. Subjective norms also had a substantial influence on intentions; encouraging safety communications and fostering positive safety climate could promote the favourable subjective norms. The introduction of attitudinal ambivalence in this research showed its ability to account for the prediction of intention and behaviour and will be the first step in understanding the occurrence, the expansion, and the impact of ambivalent attitude in construction worker groups.

The main contribution of this research is the use of psychological approach to provide a clear picture of why and how unsafe behaviour happens. As a partial mediating factor, attitudinal ambivalence provided an explanation of the complex and evolving decision-making process behind unsafe behaviour under multiple information sources and conflicting environments.

Appendix

Questionnaire of Workers' Safety Attitude and Behaviour (Note: This Is a Translation of the Original Questionnaire in Chinese)

Dear colleagues,

Thank you very much for taking your time in this survey.

This is a research survey on workers' safety attitude and behaviour. It will help us get to know your safety views, attitude and behaviour better, and eventually it will help the construction industry and yourself. We sincerely hope you could treat it carefully and tell us your real thoughts. We assure you that you are not required to put your name anywhere in the survey, and your answers will be treated in full confidential and used only for research.

Your answers are valuable. Thank you again for your cooperation!

Part 1: Personal Information

Please tick "√" when it fits your situation.

(1) Your age: ☐ under 20 ☐ 20~29 ☐ 30~39 ☐ 40~49 ☐ over 50

Table 5: Safety attitude scale.

			Safety attitude (not shown on paper)			
SA1	1. There are various and complex risks in construction, are you familiar about the risks that can be harmful to your health during work:	Very unfamiliar	Not very familiar	Somehow familiar but not very much	Familiar	Very familiar
SA2	2. Even experts did not agree on whether construction risks could be avoided. I think risks:	Cannot be avoided at all	Almost cannot be avoided	Some can be avoided and some cannot	Basically can be avoided	Definitely can be avoided
SA3	3. My coworkers and I generally believe that correctly wearing PPE ( ) avoid accidents	Cannot	Basically cannot	Sometimes can and sometimes cannot	Generally can	Can effectively
SA4	4. I believe to correctly wear PPE is	Not necessary	Impossible	Not sure	A should-do	A must-do
SA5	5. The safety rules are complicated, are you familiar with all PPE supposed to wear in the work:	Very unfamiliar	Not very familiar	Somehow familiar but not very much	Familiar	Very familiar
SA6	6. It could be complicated, are you familiar with all the situations to wear PPE?	Very unfamiliar	Not very familiar	Somehow familiar but not very much	Familiar	Very familiar
SA7	7. My coworkers and I are ( ) to take trainings on how to wear PPE correctly	Happily willing	Willing	Not sure	Reluctant	Not willing
SA8	8. Wearing PPE correctly, I feel ()	It would be better if I do not have to	It would not be a problem if I do not wear it	Sometimes, safe	Most of the time safe	Very safe
			Attitudinal ambivalence (not shown on paper)			
AA1	9. Wearing PPE could be:	Very comfortable	Comfortable	Not sure	Uncomfortable	Very uncomfortable
AA2	10. Many people are not used to wearing PPE, and I:	Am used to it	Am getting used to it	Am not sure	Am not very used to it	Am not used to it
AA3	11. I ( ) the experience of not wearing PPE and accidents happened	Have not encountered or heard	Have not encountered	Not sure	Have heard	Have encountered
AA4	12. It takes ( ) to finish the work if I keep PPE on:	Much longer	A little longer	Not sure	A little faster	Much faster
AA5	13. I can perform better if I wear PPE	Sure	I think so	Not sure	Probably not	No
AA6	14. My coworkers and I feel ( ) working in this site	Very dangerous	Not very safe	Not sure	Safe	Very safe
AA7	15. My coworkers and I ( ) in learning how to wear PPE	Do not think it necessary	Are not very interested	Not sure	Are interested	Are very interested
AA8	16. I ( ) the experience of not wearing PPE and accidents happened	Have not encountered or heard	Have not encountered	Not sure	Have heard	Have encountered
			Subjective norm (not shown on paper)			
SN1	17. I think good relationships with my coworkers ( ) help me wear PPE correctly	Is impossible to	Is likely impossible to	Not sure	Possibly will	Will
SN2	18. I think good relationships with my supervisors ( ) help me wear PPE correctly	Is impossible to	Is likely impossible to	Not sure	Possibly will	Will

Table 5: Continued.

SN3	19. If I failed to wear PPE correctly, my coworkers ( ) remind me	Would	Some would	Sometimes would	Basically would not	Would not
SN4	20. I think my family ( ) hope me to wear PPE correctly	Do not care to	Might	Somewhat	Generally	Greatly
SN5	21. Do you have the experience that you had a tense relationship with the foremen and not able to wear PPE correctly?	No	Barely not	Not sure	Possibly yes	Definitely yes
			Perceived behavioural control (not shown on paper)			
PBC1	22. I am ( ) to wear PPE correctly	Not confident	Not very confident	Not sure if I will	Confident	Very confident
PBC2	23. My coworkers and I believe that without mandatory rules, we ( ) wear the PPE correctly	Will still	May	Not sure if we will	May not	Will not
PBC3	24. I ( ) felt that it does not matter if I do not follow safety guidelines for a few times during work	Never	Barely	Not sure	Possibly	Have
PBC4	25. I ( ) wear PPE when I am exhausted	Will not	Will possibly not	Am not sure if I will	Will possibly	Will definitely
PBC5	26. I am ( ) given the information I need to follow safety guidelines	Fully	Mostly	Partly	Barely	Not
PBC6	27. If no one reminds me, I ( ) wear PPE	Will not	Mostly will not	Sometimes will	Basically happy to	Am happy to
PBC7	28. I have to keep wearing PPE correctly:	Definitely	Mostly	Not sure	Impossible	Not necessarily
			Intention (not shown on paper)			
INT1	29. I ( ) to wear PPE correctly in the next four weeks	Will not	May not	Not sure	May	Will
INT2	30. In the last two months, I feel like everyone has ( ) worn PPE correctly	Not	Not always	Not sure	Occasionally	Always
INT3	31. In the last six months, I feel like everyone has ( ) worn PPE correctly	Not	Not always	Not sure	Occasionally	Always

(2) Your education: ☐ Primary school ☐ Middle school ☐ High school ☐ Occupational education ☐ University or higher

(3) You have been working in construction industry for: ☐ 0~3 years ☐ 4~7 years ☐ 8~10 years ☐ More than 10 years

(4) You have been working on this site for: ☐ Less than 6 months ☐ 6 to 12 months ☐ 1 year or more

(5) Your trade: ☐ Bar benders ☐ Concrete workers ☐ Frame workers ☐ Electronics ☐ Labourers ☐ Carpenters ☐ Drivers ☐ Others

Part 2: Safety Attitude Scale (Table 5).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Research Article

Improved HFACS on Human Factors of Construction Accidents: A China Perspective

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Human errors are one of the major contributors of accidents. In order to improve the safety performance, human errors have to be addressed. Human Factors Analysis and Classification System (HFACS) has been developed as an analytical framework for the investigation of the role of human errors in aviation accidents. However, the HFACS framework did not reveal the relationships describing the effect among diverse factors at different levels. Similarly, its interior structure was not exposed. As a result, it is difficult to identify critical paths and key factors. Therefore, an improved Human Factors Analysis and Classification System in the construction industry (I-HFACS) was developed in this study. An analytical I-HFACS mechanism was designed to interpret how activities and decisions made by upper management lead to operator errors and subsequent accidents. Critical paths were highlighted. Similarly, key human factors were identified, that is, "regulatory factors," "organizational process," "supervisory violations," "adverse spiritual state," "skill underutilization," "skill-based errors," and "violations." Findings provided useful references for the construction industry to improve the safety performance.

1. Introduction

Construction work is highly associated with safety hazards. In America, fatal injuries of the private construction sector were 937 in 2015, with 4 percent rise, which was the highest since 2008, ranking first among the 16 industry sectors [1]. In Britain, the rate of fatal injuries in the construction industry was more than 3.5 times the average mortality rate in all sectors in 2015 [2]. This is especially a major concern in developing countries [3]. According to the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD), the new building area in China is more than 2 billion square meters, being the largest in the world. In 2016, the number of construction accidents in China rose 124.8% to 3523. This has shown that the safety in construction activities is severe and a significant challenge in China.

Health and Safety Executives concluded that human errors were responsible for over 80 percent of accidents [4]. Human errors were generally defined as "...situations where a sequence of planned events of spiritual or physical activities haven't been able to achieve the desired outcomes, and we can't attribute these failures to the intervention of some change agency" [5]. It is well recognized that human errors should be paid attention to in construction projects [6]. By settling human errors, statistics on accidents cases, injuries, and deaths in the construction sector are expected to be decreased [7].

There are two aspects of human errors-related issues [8]: the individual approach and systematic approach. Traditionally, the individual approach focuses on unsafe acts, which are viewed as resulting primarily from abnormal psychological issues such as lack of attention, negligence, carelessness, shortage of motivation, and recklessness. The systematic approach [9] views human errors as a consequence, rather than a cause. In the systematic approach, human errors have roots not lying in the aberration of human nature but in "upstream and latent" factors of the system [8, 10]. Compared to the systematic approach, the individual approach does not carry out the analysis of mishaps and near misses in detail. As a result, recurrent error traps will not be uncovered until

Table 1: Types of human-related accident analysis methods [31].

	Provision of a set of causal factors	No provision of a set of causal factors
Micro		Type I (e.g., root cause analysis techniques such as change analysis, barrier analysis, and event and causal factor charting)
(Partly) meso and micro	Type II (e.g., HPES, K-HPES, HPIP, CREAM, SOL, TRACEr, and HFIT)	
Meso and micro	Type IV (e.g., HFACS)	
Macro and meso and micro		Type III (e.g., AcciMap and STAMP)

the occurrence. Similarly, by revolving around the individual sources of human errors, the individual approach segregates unsafe acts from the systematic environment [8].

Therefore, the system approach should be adopted to examine human errors for the construction safety improvement [11]. Wiegmann and Shappell suggested that HFACS (Human Factors Analysis and Classification System), which was initially developed for aviation, was an open tool of systematic analysis and should be adjusted according to specific characteristics of different industries [12]. However, Dekker suggested there were some confusions between classification and analysis in HFACS. The simple categorization of failures does not have explanatory and persuasive power [10]. It is necessary to find the impact mechanism and interior structure of this framework. What is more, construction projects are resource-consuming. Constrained by limited resources, managers and researchers have devoted to effective allocation and utilization of resources [13]. To solve the distribution problem with limited resources, it is essential to identify critical paths, key factors, and priorities for managers [14]. Therefore, the aims of this study are (1) to develop the modified and improved HFACS within the Chinese construction industry context and identify the impact mechanism and interior structure of it and (2) to identify the critical paths and key human factors affecting high frequency of occurrence of accidents in the construction industry based on this model.

2. Literature Review

Previous studies have examined factors of safety accidents from various perspectives. Chiu and Hsieh pointed out that human errors may be divided into two types: active human errors and latent human errors [15]. In 1950, Heinrich et al. advocated that accidents were caused by unsafe acts and unsafe conditions [16]. Motivated by this idea, construction safety management has concentrated on eliminating both areas [17]. Unsafe acts have been recognized as the direct and active reason for construction accidents [18]. As unsafe acts are often intentional, cognitive theory aimed to explain human acts by understanding thought processes [19]. A few notable research studies on workers' spiritual processes were taken towards unsafe acts, such as attitudes towards behaviors and risk perception [20].

Reason clearly indicated that, in the most cases, unsafe acts (active human errors) were influenced by latent conditions before producing a loss [21]. Many research studies have investigated different working conditions and identified condition risk factors in construction projects influencing unsafe acts [22, 23], such as inappropriate ground conditions and an unacceptably noisy or crowded environment [24, 25]. And Krivit et al. also suggested that most unsafe acts could also be traced back to supervision [26]. Meliá and Becerril demonstrated that factors related to the supervisors were cited by workers as important causes of their occupational stress in the construction sector [27]. Indeed, evidence has shown that organizational factors shaped the context that contributes to human errors [28]. Khosravi et al. identified the organizational factors, including policy and plan, safety climate and culture, project and job design, and resource management, having high evidence of associations with unsafe acts in the construction sector [29].

A critical review of the previous studies of human errors showed that these various "upstream and latent" factors (e.g., site conditions, supervisions, and organizational factors) contributed to human errors. While these active and latent human errors are recognized related and intermingled, they were examined separately from one another in practice and did not provide a holistic framework that may help project managers handle the various policy, process, and personnel aspects that may affect construction safety [30].

A number of human-related accident analysis methods have been developed to assist in comprehending how human errors occur. Yoon et al. classified these methods into four types in Table 1 by two criteria [31]. Reviewing human-related methods, we found HFACS (Human Factors Analysis and Classification System) provided a predetermined set of causal factors by incorporating various "upstream and latent" factors. Wiegmann and Shappell argued that HFACS had advantages of diagnosis, reliability, and comprehensiveness, particularly in large-scale and complex accidents [12]. One advantage of HFACS is its use of generic terms and descriptors that are applicable to a range of industries. However, HFACS was initially developed for aviation and the definition of each term may be diverse according to different industries. Many recent studies have evaluated the effectiveness of HFACS in various safety-critical domains which were aviation [32], navigation [33], coal mine [34], railway [35], and so on. Thus, HFACS provides a useful tool for analyzing human factors of construction accidents and can be adjusted and improved according to specific characteristics of the construction industry.

The fundamentals of HFACS lied in the theory of Reason's GEMS which was often referred to as the "Swiss cheese model" [36]. GEMS depicted errors as arising from holes at four levels, beginning with the operator, and working up through the system to organizational conditions [36]. According to this model, active failures combine with latent conditions upstream in the organization to lead to an accident. Active factors occur just before the accident and have traditionally been most often cited as the cause of an accident. Latent factors often exist for years and may never be associated with an accident or identified as a safety issue, unless they are explicitly examined [36]. The advantage of this model is bringing these human errors together into a systematic and integrated framework. However, "Swiss cheese model" did not explain the exact meaning of the "hole" in the cheese; that is, there was no illustration of what the defects of each level were. To remedy this, Wiegmann and Shappell developed HFACS, in which unsafe acts were produced by a group of underlying and potential factors of the unsafe precondition and unsafe supervision and organization [37]. Unsafe acts were active factors, involving violations and errors. The preconditions draw a picture of the substandard and aberrant conditions and performances of operators. Unsafe supervision traced the cause-effect chain of events spawning unsafe acts up to front-line supervisors. Organizational influences involved failures in activities and decisions made by the upper management that had an impact on the performance of the supervision, along with preconditions and operations of workers.

In the construction industry, Hale et al. have proposed an extended HFACS framework based on a study of a small sample reported from the UK Health and Safety Executive [38]. However, that study did not reveal the relationships among diverse factors at different levels and identify critical paths and key factors in the proposed framework. First, the traditional HFACS has a few limitations. Dekker suggested that the framework merely repositioned human errors by shifting them from the forefront to higher up in the organization instead of finding solutions for them [10]. To remedy this, several studies have revealed the relationships describing the effect among diverse factors at different levels in the framework [39]. However, they did not explain whether the factors at the same level may also be associated. Second, it is well known that a construction project is the process of resource consumption. Especially for large projects, the type of consumption of resources is various and the quantities are large [13]. The process of the resource allocation seeks to find an optimal allocation of a limited amount of resources to a number of tasks for optimizing their objectives subject to the given resource constraint. During the construction process, the project cannot be sustained to meet the various requests for resources due to the interference of various uncertain factors. The limited-resource allocation problem arises in many construction projects when there are different limitations on the amount of resources available to the managers [14]. It is significant to rationally make use of the resources in the construction process and allocate the resources in the key areas that can raise the level of safety [40]. To solve the distribution problem with limited resources, the objective is to assign priorities to the project activities based on measures obtained from the critical paths and key factors [14].

3. Methodology

3.1. Research Design. Figure 1 shows the research process and methods in this study. The entire research process consisted of two steps: in stage-1, the initial HFACS framework in the

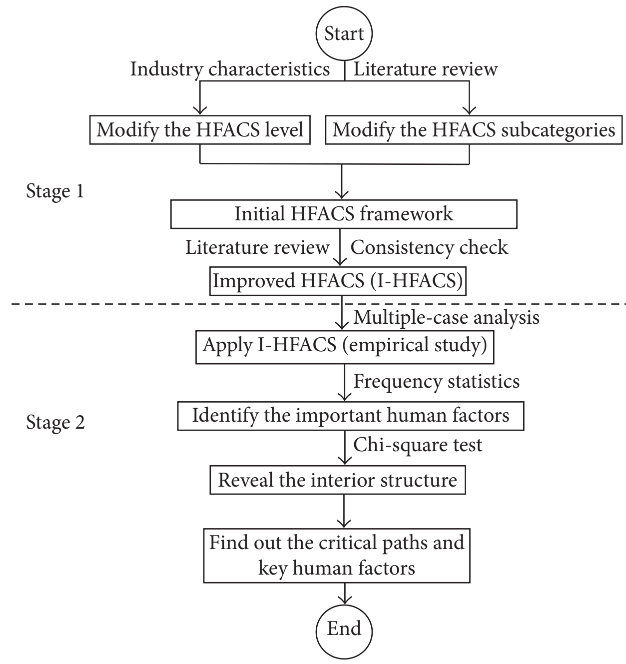

Figure 1: The research framework.

construction industry was developed through modifying the HFACS level and subcategories based on a critical review of existing studies. Consequently, a literature review was carried out to identify the definition and specific performance of each subcategory based on the initial HFACS framework, and consistency check was done to confirm the final improved HFACS framework (I-HFACS). Then, in stage-2, an empirical study of 150 accident cases (the selection of 150 sample cases is shown in Section 3.3.1) was conducted to collect data applying the I-HFACS framework. Subsequently, frequency analysis was undertaken to identify the relatively important human factors. Lastly, reviewing available statistical tests (as seen in Table 2), the chi-square test was selected to test the associations between the subcategories at the adjacent levels and the same levels because of the binomial data in this study. Thus, the chi-square test was conducted to reveal the interior structure. Based on the important human factors identified in frequency analysis and the associations between subcategories, we could further identify the critical paths and key human factors.

3.2. Consistency Check. Olsen and Shorrock suggested that different observers may have inconsistent ideas in the same phenomenon among themselves [42]. Meanwhile, there might be incongruous understanding between items of the I-HFACS framework and construction safety accident reports. This may lead to different results from different analysts to the same accidents. Therefore, analysts need to be trained to ensure their results are consistent, which paves the way for the subsequent empirical study. The procedure of consistency check is shown in Figure 2.

The definition of subcategories of the initial version of the I-HFACS framework was drawn from the literature review. First, a random selection without repetition of

Table 2: The category of statistical tests [41].

Goal	Type of data: Measurement (from Gaussian population)	Rank, score, or measurement (from non-Gaussian population)	Binomial (two possible outcomes)	Survival time
Comparing three or more unmatched groups	One-way ANOVA	Kruskal–Wallis test	Chi-square test	Cox proportional hazards regression
Comparing three or more matched groups	Repeated-measures ANOVA	Friedman test	Cochran's Q	Conditional proportional hazards regression
Testing association between two variables	Pearson correlation	Spearman correlation	Chi-square test	
Predicting value from another measured variable	Simple linear regression			Predicting value from another measured variable
Predicting value from several measured or binomial variables	Multiple (non)linear regression		Multiple logistic regression	Cox proportional hazards regression

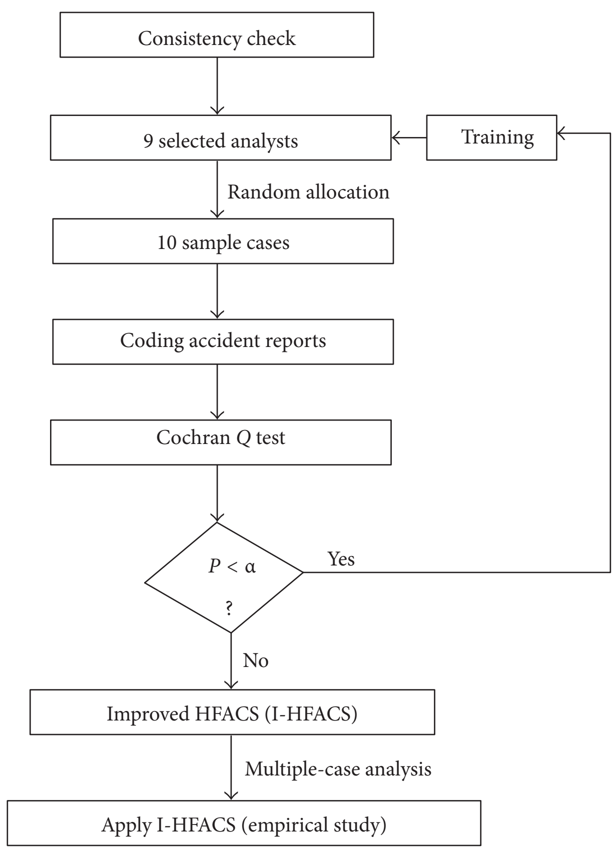

Figure 2: The procedure of consistency check.

10 Chinese construction safety accident reports from 150 sample cases (the selection of 150 sample cases is shown in Section 3.3.1) was regarded as research objects. The procedures to conduct random selection without repetition by Excel were described as follows: (1) code the 150 sample cases from 1 to 150 and suppose the group from which the selection has to be made is in A1:A150; (2) then, in the adjacent column, enter the formula = RAND(); and (3) in the next column over, enter the formula = INDEX($A$1:$A$150, RANK(B1, $B$1:$B$150)). Thus, a random selection without repetition of 10 cases was found. Second, 9 postgraduates were sent to obtain and analyze data. These 9 postgraduates have studied engineering management for 4 years in the stage of undergraduate and studied construction safety for 2 years in the stage of postgraduate. They have investigated construction sites and been trained together on how to use the framework. The training programs contained a detailed introduction, explanation, and description of the I-HFACS framework, each I-HFACS level, and individual I-HFACS subcategory. Each analyst independently worked on the 10 case accidents and worked on each accident report iteratively. For each analyst, if the cause of the sample case was related to some subcategory of the I-HFACS framework, the analyst coded "1." If not, the analyst coded "0." Each I-HFACS subcategory was calculated a maximum of one time for each case. Thus, this count was simply conducted as an indicator of the existence or non-existence of each subcategory within a given sample case. Finally, Cochran's Q test was conducted to determine the improved HFACS framework (I-HFACS). In Cochran's Q test, if $P < \alpha$, it means that 9 analysts had not yet reached an agreement on the perception of each subcategory. As a result, 9 analysts should be retraining and the definition of each subcategory would be modified until $P > \alpha$. Ultimately, the improved HFACS framework (I-HFACS) was confirmed based on which multiple-case analysis was applied.

3.3. Multiple-Case Analysis

3.3.1. Sample Cases. The procedure of data collection is shown in Figure 3. Firstly, severe construction safety accidents between 2000 and 2016 were obtained from MOHURD, in a total of 430 cases. The severe construction safety accident was defined as the accidents of more than 3 and less than 10 deaths or more than 10 and less than 50 seriously injured people or direct economic losses being between 10 million and 50 million RMB (between 1.6 million and 8 million USD). However, 150 accident reports out of 430 were available in the public domain. For relatively small population (less than 1000), a larger sampling rate (about 30%) is needed in the demand of higher accuracy [43]. The 150 cases were 34.9% of the 430 cases, meeting the sampling rate. Thus, 150 case

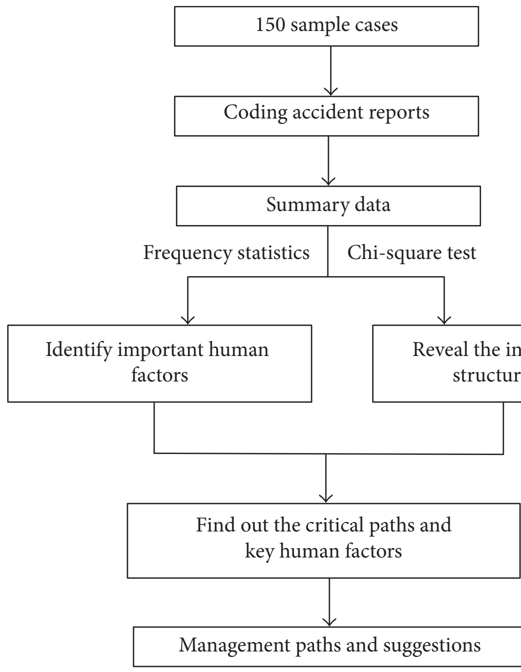

Figure 3: The procedure of data collection.

Table 3: The types of 150 construction safety accident cases.

Accident type	Object strike	Mechanical damage	Lifting injury	Electric shock	Fire	High-altitude falling	Collapse	Water inrush	Explosion	Poisoning
Accident number	2	9	10	1	3	23	92	2	3	5
Rate	1.33%	6.00%	6.67%	0.67%	2.00%	15.33%	61.33%	1.33%	2.00%	3.33%

reports were taken as research objects. The types and number of 150 construction safety accident cases are presented in Table 3. Collapse and high-altitude falling were the main types of construction accidents. In particular, collapse accounted for 61.33% of the total number of severe accidents.

3.3.2. Data Analysis. Secondly, based on the I-HFACS framework, 9 analysts, who shared a common and identical understanding of the classification process and I-HFACS subcategories, coded these 150 sample cases. The principle of the coding was the same as in Section 3.2. Scores of 9 analysts were compiled. If each accident case scored more than 6 points in the same subcategory, which means 60% of the 9 analysts believed that the cause of the construction safety accident case was related to the subcategory of the I-HFACS framework for accident causes (more than 60% of the total is the majority or the greater part in Wikipedia), we code "1," otherwise "0."

Then, the data collected from the 150 cases were counted. Subsequently, frequency analysis was conducted to identify the relatively important human factors. The chi-square test was undertaken to highlight the associations between the subcategories at the adjacent levels and the same levels in the I-HFACS analytical framework. Lastly, based on the important human factors identified in frequency analysis and the associations between subcategories, the critical paths and key human factors were consequently identified.

4. Development of the Improved HFACS (I-HFACS)

4.1. One Level Added and Some Subcategories Adjusted. The initial HFACS framework was modified according to specific characteristics of the construction industry, for example, the added level and the adjustment and modification of categories and subcategories (Figure 4). The changes from the original model are shown in grey boxes.

The fifth- (or the top-) level "external factors" were added, which meant to capture the impact of safety deficiencies outside the scope of organizations. Meanwhile, "external factors" include "regulatory factors" and "economic/political/social/legal environment." Reinach and Viale noted that the regulatory environment contributed to an accident, even though indirectly [44]. The inadequacy of the regulatory environment may lay a breeding ground for inertia and fluke mind of main bodies in construction [45]. Besides, Khosravi et al. identified the role of the economic/political/social/legal environment in unsafe acts [29]. The response of the client under these factors will present a few constraints, in which parties involved in the project have the potential to act unsafely. The process of cause and effect tends to restrain front-line operators through inapposite construction plans and control programs, resulting in improper preconditions and actions [25].

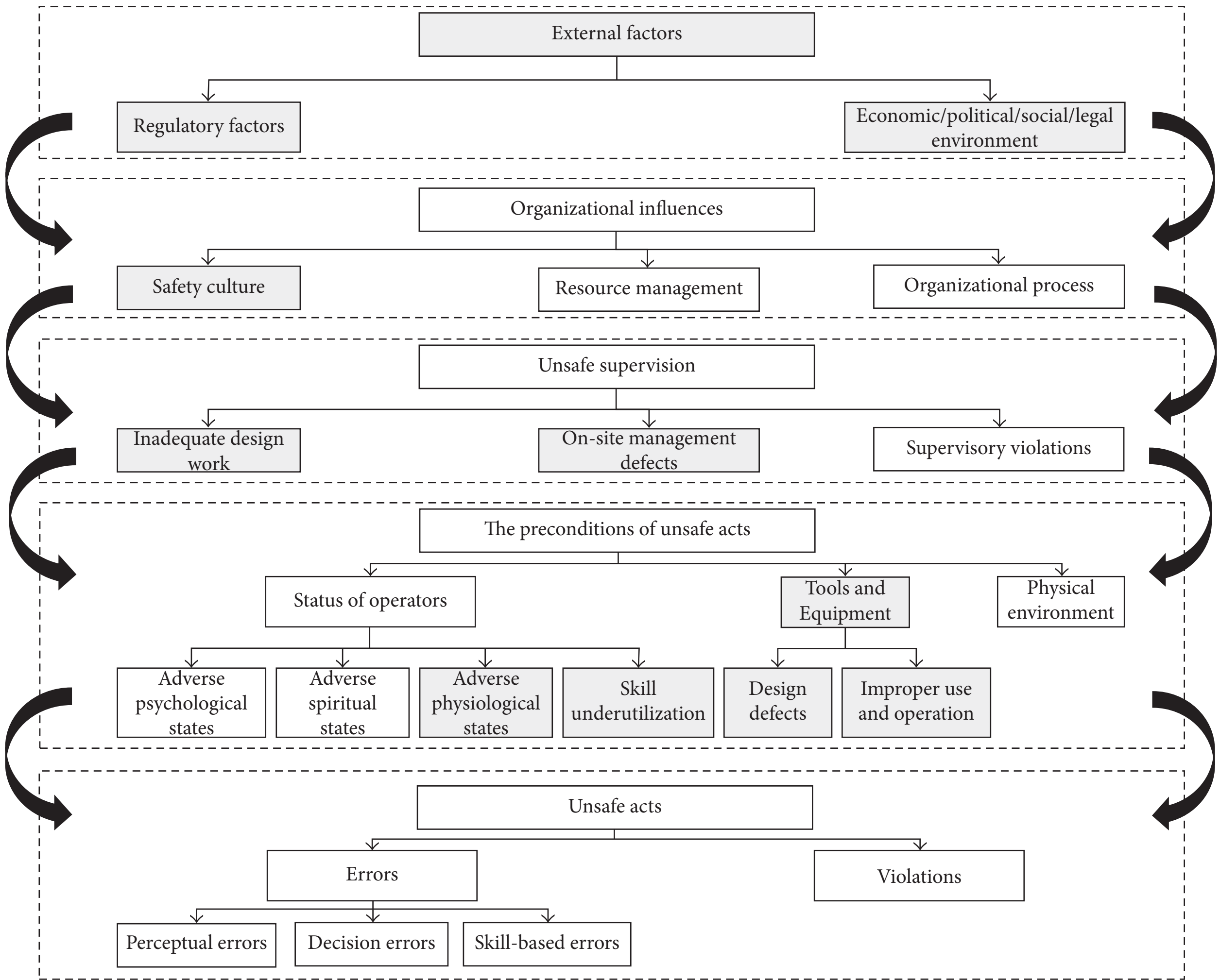

Figure 4: The initial HFACS framework in the construction industry.

"Organizational climate" was replaced with "safety culture" in level 4. In fact, there has always been confusion between safety culture and safety climate [46]. Teo and Feng argued that safety climate was not an alternative to safety culture [47]. Safety climate is the outward appearance of safety culture and a time-dependent phenomenon, prone to change and relatively unstable [48, 49]. Safety culture is the outcome of group and individual perceptions, values, competencies, and behavior patterns. The characteristics of organizations with a positive culture are communicating based on mutual trust, through identical recognitions of the significance of safety and conviction in the effectiveness of precautions [50]. Therefore, "organizational climate" was replaced by "safety culture."

In the third level of HFACS, there were 2 changes: (1) merging the three subcategories ("inadequate supervision," "planned inappropriate operations," and "failure to correct a known problem") of the traditional HFACS into "on-site management defects." Shohe and Laufer suggested supervisors were the role players who help with the organization and promotion of daily construction management [51]. Kim et al. indicated that site supervision, plan management, and correcting a known problem were three important functions of on-site management [52]. Thus, we merged the three subcategories into "on-site management defects"; and (2) adding a subcategory "inadequate design work" to this level. Many researchers summarized management performance of project managers into system design and supervisory control [53]. Having the proper planning in conjunction with security management in the construction prophase can greatly reduce the occurrence of accidents [54, 55]. Qingren et al. pointed out that design work of project managers was to provide guidance for construction workers by making a variety of specifications, procedures, schemes, and plans [56]. Therefore, this subcategory (i.e., "inadequate design work") was added in this study.

The second level of the traditional HFACS included "environmental factors" (physical environment and technological environment), "condition of individuals" (adverse mental states, adverse physiological states, and physical/mental limitations), and "personal factors" (crew resource mismanagement and personal readiness). According to the characteristics of the construction industry, it is well recognized that unsafe acts of operators should be examined from the perspective of "man-machine environment" [57, 58]. The specific changes of the subcategories included

Table 4: Cochran's Q test about the identical effects by the 9 analysts.

Accident code	1	2	3	4	5	6	7	8	9	10
P value	0.059	0.056	0.113	0.064	0.080	0.082	0.077	0.053	0.064	0.067

the following: (1) "condition of individuals" and "personal factors" were merged into "status of operators." "Status of operators" involved "adverse spiritual states," "adverse psychological states," "adverse physiological states," and "skill underutilization." In the construction industry, apart from psychological and physiological states [59, 60], skill underutilization was also found to cause accidents [61]. Many researchers maintained that spiritual states and psychological states were the same thing. However, according to the confusion in psychology (the word "psychology" that originates from psyche is regarded as "spirit") and based on the localization research orientation (the psychology belongs to the inner world of one's mind, while the spirit is the outer one), this study considered that "psychology" equating to "spirit" was unsuitable in psychology [62] and "status of operators" should involve "adverse spiritual states" and "adverse psychological states"; (2) "tools and equipment" involved "design defects" and "improper use and operation." Numerous studies reported that man-machine ergonomics was overlooked in the design of mechanical equipment and safety warning signs, which did not match with behavior rules of workers' sense of touch, attention, and reaction speed [58, 63]. In addition, Choudhry and Dongping found that workers may go against operating instructions because of time and labor savings [64]. Therefore, "tools and equipment" included "design defects" and "improper use and operation"; and (3) "environmental factors" in the traditional HFACS included the technological and physical environment. However, in the construction industry, "environmental factors" refer more to the physical environment of the construction site. Similarly, the technological environment emphasizes on the quality of inspection and maintenance and equipment operability which were involved in "tools and equipment." Thus, environmental factors of the traditional HFACS were changed into "physical environment."

4.2. The Definition of Each Subcategory. Having developed the initial HFACS framework in the construction industry, the improved HFACS in construction (I-HFACS) based on the initial HFACS framework was needed to be established. Through a critical review of literature [18,38,64–67], this study identified the initial version of the I-HFACS framework according to the following 3 principles: (1) all detailed items reflect the subcategory they belong to; (2) there is a distinct division among different detailed items; and (3) all detailed items are clear and not ambiguous. Then, the consistency check was carried out to confirm the final improved HFACS framework (I-HFACS). Cochran's Q test was undertaken in this step to assess whether different observers in the same phenomenon had consistent results amongst themselves (i.e., interobserver variability). For the significant level α, if P value is more than α, there are identical effects among the 9 analysts. If P value is less than α, there are not [68]. Cochran's Q test was run in SPSS 19.0. We defined $\alpha = 0.05$; the analytic results based on the initial version of the I-HFACS framework showed "P value $= 0.02 < \alpha = 0.05$." Based on analytic results, the initial version of the I-HFACS framework was adjusted and 9 analysts should be retraining. Then, 9 analysts performed a second round of accident analysis. After 3 rounds of iterations, the analytic results showed "$P = 0.059 > \alpha = 0.05$," which came to an agreement on the perception of each subcategory. Finally, based on the ultimate version, 9 analysts analyzed the 10 construction safety cases. The results are shown in Table 4. It demonstrated that all analysts had identical effects, indicating the ultimate version of the I-HFACS framework was the effective basis for analysis of construction safety accidents. The final version of the I-HFACS framework is shown in Table 5.

4.3. The Interior Structure. The chi-square test was conducted to estimate the statistical strength of associations between subcategories at the adjacent levels and the same levels of I-HFACS. In chi-square ($\chi 2$) analysis, if P value is small ($P < 0.05$), the null hypothesis (H_0) will be rejected and the alternative hypothesis (H_a) should be accepted. This indicates there are significant associations, and vice versa. Meanwhile, effective chi-square ($\chi 2$) analysis requires less than or equal to 25 percent of theoretical frequency that has expected count less than 5, or significant Fisher's exact tests if more than 25 percent of it. Based on the theoretical assumptions of the HFACS framework, subcategories at downward levels are dependent on subcategories at upper levels and cannot adversely influence upper subcategories [69]. Higher levels in the I-HFACS are deemed to cause changes at the lower levels, thus going beyond what may be deemed a simple test of co-occurrence between subcategories [70]. Then, odds ratio (OR) was used to estimate the probability of the existence of one I-HFACS subcategory associated with another subcategory concomitantly existing. In OR analysis, when the OR value is greater than 1, it can be seen that downward-level subcategories are more likely to occur when upper-level subcategories are in place. In a more technical language, the OR value is a measure of effect size, describing the strength of associations or nonindependence between two binary data values [71]. In this study, chi-square ($\chi 2$) analysis was carried out using SPSS 19.0. We selected the associations in the condition of $P < 0.05$ and $\mathrm{OR} > 1$. These significant associations are summarized in Tables 6 and 7.

As for the analysis of upper-level and adjacent downward-level subcategories in the I-HFACS framework, analysis of the strength of associations at the "external factors" level and "organizational influences" level showed 3 pairs of significant associations ($P < 0.005$). In particular, "safety culture" was over 17 times more likely to occur when

Table 5: The I-HFACS framework.

Level 5: external factors	Regulatory factors		A: regulator cannot "reach" duty holders; B: ineffective regulators' inspections and enforcement; C: inadequate regulatory standards
	Economic/political/social/legal environment		A: insufficient laws, regulations, and policies related to construction safety; B: insufficient publicity of laws, regulations, and policies related to construction safety; C: society prioritizing other issues over safety; E: supply problems: services/materials/labor; F: restrictive economic conditions
Level 4: organizational influences	Safety culture		A: managers' lack of values and beliefs of safety; B: ineffective enterprise safety system; C: not well-organized enterprise safety organization or ambiguous responsibilities (from the corporate level)
	Resource management		A: inefficient human resources allocation and selection (from the enterprise level); B: insufficient safety training program; C: lack of safety investment and overcutting costs; D: purchase of unsuitable materials (type or size) and equipment
	Organizational process		A: ineffective procedures and contingency plan; B: excessive emphasis on other purposes rather than safety management; C: failed to fulfill the designated enterprise safety system and responsibilities; D: ineffective resource supervision and fulfillment
Level 3: unsafe supervision	Inadequate design work		A: ineffective supervisory system, safety plans, and schemes on site; B: excessive task load; C: ineffective personnel allocation and labor organization on site
	On-site management defects		A: failed to fulfill the designed work on site and responsibilities; B: failure to correct unsafe acts timely; C: ineffective potential safety hazard checking and controlling; D: ineffective track management
	Supervisory violations		A: failed to comply with company safety rules and regulations; B: violation in commanding; C: authorized unqualified working team or group to perform
Level 2: the preconditions of unsafe acts	Status of operators	Adverse psychological states	A: stress; B: abnormal feeling fluctuation; C: fluke mind, empiric mind, impulse mind, and others
		Adverse physiological states	A: physical fatigue; B: illness; C: poisoning; D: physical limitations
		Adverse spiritual states	A: distractions; B: weak safety consciousness; C: poor safety attitude; D: excessive self-confidence
		Skill underutilization	A: inadequate experience; B: inadequate safety knowledge and skills
	Tools and equipment	Design defects	A: lack of inconspicuous warnings and signals; B: lack of the consideration of man-machine ergonomics
		Improper use and operation	A: use of tools and equipment against operating specification; B: use of tools/equipment with defects; C: overload use of tools and equipment; D: not using PPE (personal protective equipment)
	Physical environment		A: dirty, chaotic, and poor work environment; B: noise/lighting/ground conditions; C: narrow space; D: insufficient ventilation and oxygen; E: poor geological environment; F: bad weather

Table 5: Continued.

Level 1: unsafe acts	Errors	Perceptual errors	A: wrong perception of equipment, environment, and personnel; B: misunderstanding of SOP (standard operating procedure)
		Decision errors	A: poor risk identification; B: exceeded ability; C: poor decision
		Skill-based errors	A: selecting the wrong method to perform; B: omitted step in the procedure; C: simplified operation procedure
	Violations		A: routine violations; B: exceptional violations

there were "external factors" issues associated with "regulatory factors." At I-HFACS level 4 and level 3, there were also 3 pairs of significant associations. Of these comparisons, over 6 times more likely, "on-site management defects" occurred in the presence of "organizational process" at the organizational level. Level 3 "unsafe supervision" and the adjacent downward-level "preconditions for unsafe acts" suggested 4 pairs of relationships. As for the OR value, "skill underutilization" was around 4 times more likely to happen in the existence of "supervisory violations." There were 6 pairs of evident relationships between level 2 and level 1. Particularly, inspection of the associated odds ratios showed more than 4.5 times increase in the likelihood of "skill-based errors" in the presence of "skill underutilization," and "perceptual errors" were around 4 times more likely to emerge when "poor physical environment" existed.

As for the analysis of the same-level subcategories in the I-HFACS framework, there were 6 pairs of significant associations existing. Of these comparisons, the OR values of "regulatory factors × economic/political/social/legal environment," "adverse physiological states × physical environment," and "adverse spiritual states × skill underutilization" were relatively high, describing the relative high strength of associations.

5. Understanding the Human Factors by Applying I-HFACS

5.1. The Identification of Important Human Factors. In statistics, the absolute frequency of each I-HFACS subcategory was the number of times the I-HFACS subcategory occurs in the 150 sample cases. There were a total of 1308 instances of failures indicating the contributing factors in 150 sample cases by the use of the I-HFACS framework. Statistical analysis results showed that 294 instances of errors, 22.5 percent of all, were found at the "unsafe acts" level. Failures at this level were implicated in 96.7% (145) of accidents. The most frequent subcategories at the "unsafe acts" level were skill-based errors (64%) and violations (78.7%). There were 344 (26.2%) instances of failures in total, with 91.3% (137) of all accidents analyzed at the "preconditions for unsafe acts" level. The preconditions most commonly entailed were "adverse spiritual states" (67.3%), followed by "skill underutilization" (51.3%). At level 3 "unsafe supervision," there were 323 (24.7%) instances of failures, involved in 100% (150) of sample cases. All factors at level 3 were very generally existing, with "on-site management defects" (94.7%), "supervisory violations" (65.3%), and "inadequate design work" (55.3%). At the "organizational influences" level, 239 (18.3%) instances of failures were on the record, involved in 87.3% (131) of sample cases. The most frequent factors of level 4 were "organizational process" (65.3%) and "safety culture" (56%). In the data set, failures at the "external factors" level were 108 (8.3%) instances, with "regulatory factors" (64%) being the most common factor in level 5, implicated in 64.7% (97) of all accidents analyzed.

The results in Figure 5 indicated that firstly the addition of added level 5 in this study, external factors, was of significance. Meanwhile, all levels made a great difference to construction accidents, and human factors in a low level accounted more for contribution of accidents, especially level 3 unsafe supervision. Then, this study defined the relatively important subcategories using the Pareto principle. The 11 important factors reflecting significant information are demonstrated in Figure 6. A total of 1042 frequencies were around 80 percent of the whole 1308 instances of human errors according to the Pareto principle. These important human factors were "regulatory factors" in level 5, "safety culture" and "organizational process" in level 4, "inadequate design work," "on-site management defects," and "supervisory violations" in level 3, "adverse spiritual states," "skill underutilization," and "improper use and operation" in level 2, and "skill-based errors" and "violations" in level 1.

Note that I-HFACS levels may add up to more than 100% as more than one subcategory at a given level can be identified for each case.

5.2. The Critical Paths and Key Human Factors. Based on the 11 important human factors identified in frequency analysis and the associations between subcategories, we could further identify the critical paths and key human factors. Unsafe acts (human errors) are the direct factors and responsible for over 80 percent of accidents, of which "skill-based errors" and "violations" are the key factors in level 1 [4]. For the reason that latent factors are hard to be associated with an accident or explicitly examined [36], we can track key latent factors on the basis of the key human errors that have been identified [69]. Then, "adverse spiritual states" and "skill underutilization" were defined as the key human factors in level 2, which associated with the key factors in level 1. In level 3, although "inadequate design work" had the association with "supervisory violations," the OR value of which indicated a relatively low effect size. And "supervisory

Table 6: Significant chi-square test of associations and associated values of OR for the analysis of upper-level and adjacent downward-level subcategories in the I-HFACS framework ($P < 0.05$; $\mathrm{OR} > 1$).

Significant association between upper-level and adjacent downward-level subcategories in the I-HFACS framework	$\chi 2$ test			OR value
	$\chi 2$ value	P value	Theoretical frequency (expected count < 5)	
I-HFACS level 5 association with level 4 subcategories				
Regulatory factors × safety culture	52.978	0.001	0	17.857
Regulatory factors × organizational process	6.771	0.009	0	2.500
Economic/political/social/legal environment × resource management	4.550	0.033	25%	3.633
I-HFACS level 4 association with level 3 subcategories				
Safety culture × inadequate design work	6.191	0.013	0	2.297
Organizational process × on-site management defects	6.070	0.014	25%	6.261
Organizational process × supervisory violations	4.637	0.031	0	2.143
I-HFACS level 3 association with level 2 subcategories				
Inadequate design work × adverse psychological states	6.635	0.010	0	2.940
Inadequate design work × adverse physiological states	4.867	0.027	0	3.962
Supervisory violations × adverse spiritual states	4.839	0.028	0	2.196
Supervisory violations × skill underutilization	8.904	0.003	0	2.858
I-HFACS level 2 association with level 1 subcategories				
Adverse spiritual states × decision errors	4.919	0.027	0	2.601
Adverse spiritual states × skill-based errors	12.507	0.001	0	3.603
Adverse spiritual states × violations	7.740	0.005	0	3.046
Skill underutilization × decision errors	17.324	0.001	0	5.333
Skill underutilization × skill-based errors	19.391	0.001	0	4.509
Poor physical environment × perceptual errors	7.844	0.005	0	2.819

All tests have 1 degree of freedom. All other comparisons were nonsignificant.

violations" in level 3 had effects on both the two key factors in level 2. Similarly, tracking to the upper level according to the key factors in the adjacent downward level, "supervisory violations" in level 3, "organizational process" in level 4, and "regulatory factors" in level 5 were identified the key factors. Thus, the critical path was the overall link, as seen in Figure 7, which responded positively to Reason's hypothesis and indicated actions could be taken from these "upstream and latent" factors of the system to reduce and prevent unsafe acts. The original decisions and acts at the highest levels in regulation originally had effects on "organizational processes" in level 4. Poor "organizational processes" were associated with "supervisory violations" at the level of "unsafe supervision," which showed significant statistical associations with "adverse spiritual states" and "skill underutilization" in level 2, and hence indirectly were ultimately at the root of "skill-based errors" and "violations" resulting in accidents.

6. Discussion

This study explored the application of an improved HFACS (I-HFACS) to guide accident analysis and make a better understanding of the safety implications of human errors in construction. This model enabled to accommodate not only the low level of unsafe acts (active failures) but also higher levels—the preconditions, supervision, organizational influence, and external factors (latent failures). Specifically, all subcategories within the I-HFACS framework were observed in accident cases, which indicated its ability to capture contributing factors and suggested HFACS was applicable for construction accidents if being modified and improved. Secondly, it can be observed that the added fifth (or the top) level called "external factors" was identified in accident reports, and "external factors" had influence on unsafe acts from a practical aspect. This finding suggested that it was necessary and practical to add such a highest level in the I-HFACS framework. Thirdly, the vast majority of I-HFACS subcategories had a relatively common occurrence in Figure 6, and only 2 subcategories had low frequencies of occurrence (below 10%). It can be interpreted the low numbers may report either the sensitivity of issues ("inadequate design work") or handling with a less tangible issue ("economic/political/social/legal environment"). These findings showed a strong evidence for the system approach and Reason's model of human factors.

This study also made a contribution to providing quantification evidence to reveal an analytical I-HFACS mechanism to interpret how activities and decisions made by the upper management led to operator errors and subsequent accidents. Such a mechanism also helped to identify the critical paths and key factors, illuminating the redesign of safety guidelines in the construction industry and helping construction managers with better decision-making.

"Regulatory factors" were of great importance in level 5. Feng found out that if a firm had satisfied the minimal safety

Table 7: Significant chi-square test of associations and associated values of OR for the analysis of the same-level subcategories in the I-HFACS framework ($P < 0.05$; $\mathrm{OR} > 1$).

Significant association between the same-level subcategories in the I-HFACS framework	χ^2 test			Fisher's exact test	OR value
	χ^2 value	P value	Theoretical frequency (expected count < 5)	P value	
	I-HFACS level 5 subcategories				
Regulatory factors × economic/political/social/legal environment	4.333	0.037	25%	—	6.859
	I-HFACS level 4 subcategories				
Safety culture × resource management	6.191	0.039	0	—	2.043
	I-HFACS level 3 subcategories				
Inadequate design work × on-site management defects	6.635	0.010	50%	0.009	1.107
Inadequate design work × supervisory violations	3.97	0.046	0	—	1.991
	I-HFACS level 2 subcategories				
Adverse physiological states × physical environment	4.919	0.006	25%	—	4.098
Adverse spiritual states × skill underutilization	15.092	0.001	0	—	4.145

All tests have 1 degree of freedom. All other comparisons were nonsignificant.

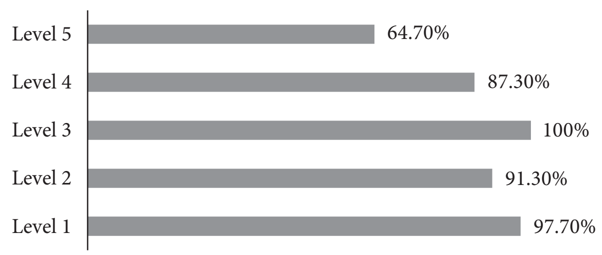

Figure 5: The total frequency comparison of each level.

requirement set by government regulations, increased investments in the more cost-effective elements (e.g., accident investigations and safety inspections) would yield much greater benefits [72]. Recurrent issues emerged from the data involved poor performance and enforcement of administrative duties. "Regulatory factors" showed a high relationship with "safety culture" in this study. Previous studies have reported that incomplete regulatory standards and poor enforcement were critical factors for determining safety culture and practices of organizations in the construction industry [38, 73]. Findings in this study demonstrated "regulatory factors" had the potential to create the conditions where organizations are able to establish effective structures. "Regulatory factors" could provide the reference guidelines for policies, norms, and culture to make organizations' safe performance and accident prevention possible [74, 75]. Therefore, enhancing the governments' regulation and making regulators' inspections and enforcement effective are required.

"Organizational process" was a key factor in level 4. It can be observed that "regulatory factors" were associated with inadequacies in the "organizational process." Poor "organizational processes" were associated with "supervisory violations" at the level of "unsafe supervision," which showed significant statistical associations with "adverse spiritual states" and "skill underutilization" in level 2, and at the end of several errors (i.e., "skill-based errors" and "violations") in operation of workers contributing to accidents, albeit indirectly. This overall link was the critical path in this study, and this finding responded positively to Reason's hypothesis; that is, failures in upper-level management had a negative impact on supervision, which successively affected preconditions and follow-up operations. For the "organizational process" subcategory, from the data of accident reports, ineffective procedures and contingency plan and excessive emphasis on other purposes rather than safety management were common failures. Previous studies also highlighted the importance of the "organizational process" affecting supervision [34]. Li and Harris argued well-developed organizational processes were essential to safety management systems [39], and safety commitment in the supervisory level was supposed to be right from the organization of upper levels [21]. Therefore, findings of this study suggested that assessment and renovation of procedures should be made and implemented for safety management.

"Supervisory violations" were a key factor at the supervision level. According to the collected data, frequent violating behaviors of supervisors in construction projects included authorizing processes that were not up to the standard, failing to enforce rules and regulations, authorizing workers to undertake dangerous construction works, and conducting supervision without qualifications. The front-line supervision will affect their workers' attitude and behavior towards safety [76]. In this study, "supervisory violations" had the associations with "adverse spiritual states" and "skill underutilization." The paths of significant associations revealed this connection. "Supervisory violations" may affect the way individuals and team members handle in the workplace, together with their ability to make decisions based on the risk perception profile of both the

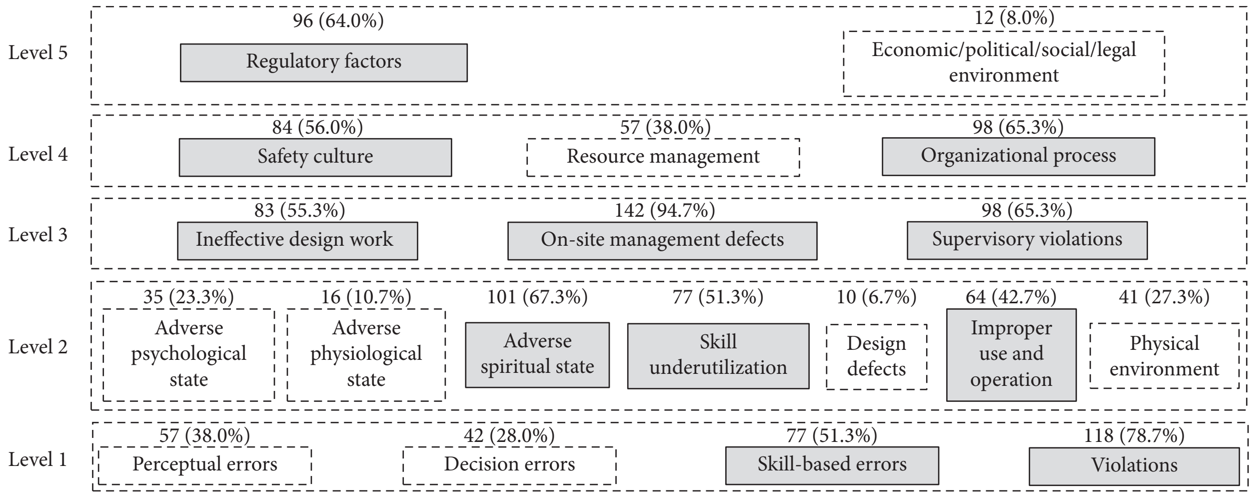

Figure 6: The relatively important factors of each level.

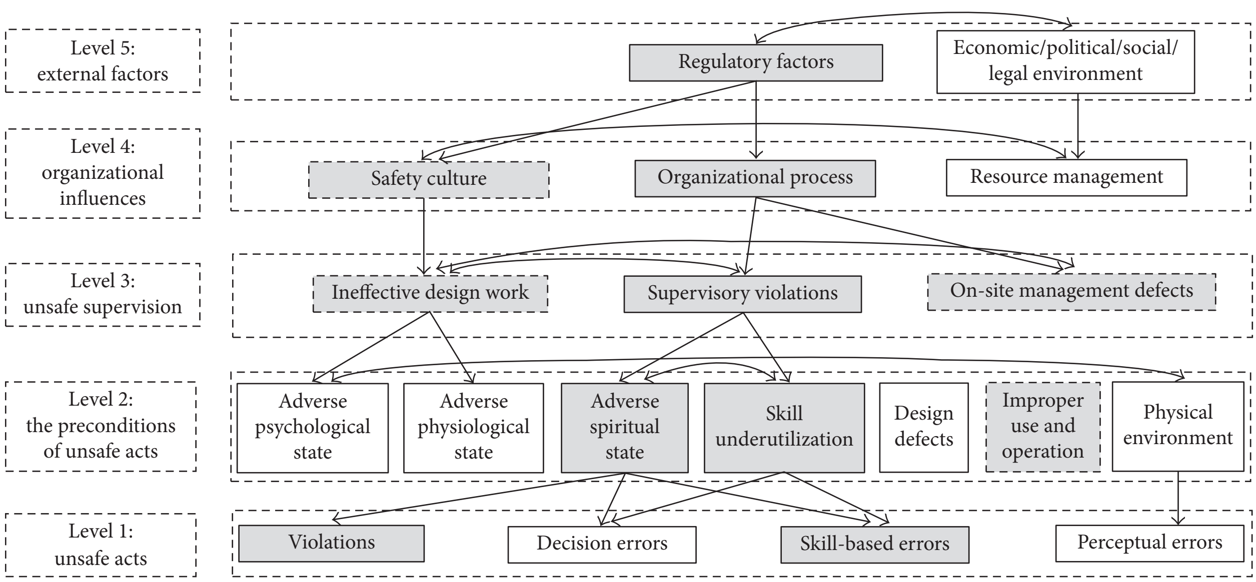

Figure 7: Critical paths and key human factors in the I-HFACS framework.

supervisor and the entire team. Li and Harris also observed that supervision was the key area and link between the upper management of the organization level and the downward precondition level [39]. Guidelines for enhancing supervision suggested ensuring the appropriate individuals were selected for supervisory roles, providing appropriate training based on the competencies required, and the continual monitoring and assessment of the supervisory system in place appear to be particularly pertinent in this case [77, 78].

The key factors of level 2 were “adverse spiritual states” and “skill underutilization,” and the issues of “skill-based errors” and “violations” were essential at level 1. Systems theory advocated that exclusions of “upstream and latent” failures were advisable for dealing with operators’ unsafe acts. Several significant relationships existed between psychological issues and errors and violations committed by construction workers. This, to some extent, supported Reason’s assertion of a “many-to-one” mapping of psychological conditions and operations [21, 69]. Wenner and Drury also believed violations and errors could be removed by ensuring a favorable physical environment of the preconditions as well [79]. Furthermore, the associations between “adverse spiritual states,” “skill underutilization,” and “supervisory violations” interpreted that “skill-based errors” and “violations” (the key factors at level 1) could be addressed by tracing the upper level of supervision. Recurrent issues in cases involve distractions, weak safety consciousness, poor safety attitude, and excessive self-confidence in the “adverse spiritual state” subcategory and inadequate experience and inadequate safety knowledge and skills in the “skill underutilization” subcategory. Moreover, Reason asserted that, in most accident databases, violations were far more common than errors, as shown in Figure 6 [69]. Violations were categorized into unintentional and deliberate violations. Results of this study showed that unintentional violations were able to be addressed by enhancing awareness though supervision and training programs. Similarly, deliberate violations have become an acceptable part of the program and even managers often took the attitude of tolerance [79]. This suggested the most efficient way to solve the issues of deliberate violations was guaranteeing the representing procedures, such as program evaluation and redevelopment of supervision and organization levels, as found in this study.

7. Conclusions

This study enriched the application of HFACS for examining construction accidents. An analytical I-HFACS mechanism was proposed to gain a better understanding of how activities made by upper management lead to operator errors. This study highlighted the critical paths, which were the overall link. The original decisions and acts at the highest levels in regulation originally had effects on "organizational processes" in level 4. Poor "organizational processes" were associated with "supervisory violations" at the level of "unsafe supervision," which showed significant statistical associations with "adverse spiritual states" and "skill underutilization" in level 2, and hence indirectly were ultimately at the root of "skill-based errors" and "violations" resulting in accidents. The result showed clearly defined statistically described paths that related errors with inadequacies at both the immediately adjacent and also higher levels in the organization and regulation. To reduce significantly the accident rate, these "paths to failure" relating to these organizational and human factors must be addressed. This suggested that only by understanding the context that induced unsafe acts could prevent the occurrence of accidents, and it would be more efficient if actions could be taken from these "upstream and latent" factors of the system.

And this study also identified the 7 key factors, "regulatory factors," "organizational process," "supervisory violations," "adverse spiritual state," "skill underutilization," "skill-based errors," and "violations," which suggested that, under the circumstances of limited resources, it would be more effective to focus on the critical paths and key factors for the improvement of construction safety performance. This study satisfied the need to redesign safety guidelines in the construction industry and helped construction managers with better decision-making. Further work can be undertaken to establish if a similar pattern of results is found in other countries and cultures.

Data Availability

The data used to support the findings of this study are from the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD).

Conflicts of Interest

The authors declare that the funding programmes do not lead to any conflicts of interest regarding the publication of the paper.

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Research Article

Does Augmented Reality Effectively Foster Visual Learning Process in Construction? An Eye-Tracking Study in Steel Installation

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Augmented reality (AR) has been proposed to be an efficient tool for learning in construction. However, few researchers have quantitatively assessed the efficiency of AR from the cognitive perspective in the context of construction education. Based on the cognitive theory of multimedia learning (CTML), we evaluated the predesigned AR-based learning tool using eye-tracking data. In this study, we tracked, compared, and summarized learners' visual behaviors in text-graph- (TG-) based, AR-based, and physical model- (PM-) based learning environments. Compared to the TG-based material, we find that both AR-based and PM-based materials foster extraneous processing and thus further promote generative processing, resulting in better learning performance. The results show that there are no significant differences between AR-based and PM-based learning environments, elucidating the advantages of AR. This study lays a foundation for problem-based learning, which is worthy of further investigation.

1. Introduction

Currently, with information technology playing an increasingly important role in various fields, people also pay increasing attention to the potential of information technology in education [1]. The construction industry is a complex environment and engineers need to deal with integrated information. Construction education has long been challenged. Traditional teaching or training is not effective enough to bridge the gap between academic and practice [2]. However, information technology enables new education strategies to be used to assist learning, one of which has gained much attention in recent years—the application of augmented reality (AR) [3]. AR is a technology that can enhance and augment reality by generating virtual objects in real environments [4]. Such coexistence of virtual and real objects helps learners visualize complex spatial relationships and abstract concepts [5].

The application of AR technology in education has been developing for more than 20 years, and AR has been applied to many fields like astronomy, chemistry, biology, mathematics, and geometry [6]. While referring to the effectiveness of the AR learning environment, it is always compared with the text-graph- (TG-) based tool for learning. While in the construction industry, apprenticeship programs are common site training methods where risk is unavoidable [7]. Besides, AR is also a significant education measure with no health or safety risks [8]. Many researchers proposed frameworks based on AR to bring remote job sites indoors [9], transform learning processes [10], or enhance the comprehension of complex dynamic and spatial-temporal constraints [11]. The use of AR technology can be an efficient way to assist learning, but there is still little quantitative evidence about the effects of AR [3]. Many researchers have evaluated the effects of AR on learning outcomes, ignoring its potential causes during the learning processes.

Eye tracking is a measurement of eye movement, which can reveal aspects of learners' learning processes [12]. Because of the use of eye-tracking software for recording and producing data, studies on learners' cognitive processes have entered a new phase [13].

TG-based and physical model- (PM-) based are common tools for construction learning and training. The authors of the present study conducted an experiment of construction class learning to (1) evaluate learning outcomes while comparing TG-based, AR-based, and PM-based environments and (2) investigate the underlying causes of the effects of the learning method from a cognitive perspective and the potential effects of AR by utilizing eye-movement data.

2. Literature Review

2.1. Does AR Facilitate or Inhibit Learning Efficiency? Multimedia learning theory suggests that appealing design features can help increase cognitive engagement and retain learner attention when it was first used [14]. Through more investigation, the visual detail in the multimedia resource can result in effective learning and instructional multimedia design [15]. According to Mayer [16], the following cognitive load theory is the basis for instructional design principles [17], cognitive theory of multimedia learning (CTML) between three kinds of processing demands that arise during learning: (1) *extraneous processing*, which is led by the manner in which the material is presented, increasing the chances that attention will be split among various information. Poor instruction may enhance this process and thus inhibit the effects of transfer learning; (2) *essential processing*, which is done to focus on presented material and is caused by the complexity of the material; and (3) *generative processing*, which is done to comprehend the material. It is caused by learner's efforts in the learning process such as selecting, organizing, and integrating. As asserted in previous studies, both extraneous and germane cognitive load can be manipulated and intrinsic cognitive loads cannot [17]. However, according to Mayer, extraneous, generative, and essential processing can be managed [18]. Furthermore, unnecessary and greater loads that stem from the design of instruction may impose extraneous cognitive loads [19]. Ineffectively searching for information may increase extraneous cognitive load and disturb essential processing. Therefore, the reasonable reduction of redundant information is an important way to reduce cognitive load and, further enhance cognitive learning. The measures include reducing extraneous processing, such as highlighting crucial materials with colors, managing essential processing, such as decomposing learning materials into several parts, and fostering generative processing [16].

AR is a useful technology with which to improve learning, as explained by the CTML [20]. It allows visual information to be registered to the real world [21]. The visual information, as instructional materials in this paper, can be designed following the CTML. Although the materials can be designed and displayed using 3D model design software, AR technology differs in that it provides immersive environments and has been developed as an immersive language learning framework that was motivated by the CTML [22]. Many scholars contend that different learning tools lead to different learning outcomes as shown in Table 1. Few researchers have paid attention to arguments of the design of AR models, the instructional material in this case. A confounding question arises: Does AR facilitate or inhibit learning efficiency by highlighting partial but critical information?

2.2. Manipulation of Extraneous Information with Various Learning Materials. AR has been proven to be a more efficient way of learning in various studies as shown in Table 1. Nonetheless, the evaluations of, compared to, conventional learning environments were basically limited to learning outcomes and, using questionnaires to examine students' subjective motivations and satisfaction [23, 24]. Because the major function of AR rests in highlighting critical information and labeling extra information as a reference for learning purposes, AR can be perceived as a measure that manipulates extraneous information processing, potentially enhancing the generative process of learning. From this perspective, previous researchers did not answer why and how AR foster learning in construction. In the educational domain, AR appears to be a smart technology with which to create attractive and motivating content. It improves the time spent on acquired learnings [25]. Moreover, an experiment revealed higher learning achievement and lower cognitive load by utilizing mobile AR application [26]. For construction education, applying AR can create a realistic learning environment without health and safety risks and enhance students' comprehensive understandings of construction equipment and operational safety [8, 10, 27]. As shown in the "control group" column of Table 1, generally, the advantages above of AR mainly come to conclusion after comparisons with conventional learning type, especially TG-based. However, the comparisons ignore the contrast with real PM-based learning materials. Besides, some of the TG-based learning material is colored as extraneous information in the experiments of Table 1, but in this paper, the TG-based model is designed according to Chinese Drawing Collection for National Building Standard Design which is not highlighted with color. The PM-based learning material is modeled as well.

2.3. Eye Tracking for Cognitive Processing Measures. Although the effect is proposed that the AR design feature leads to better learning outcomes, there is little substantive evidence that shows how this occurs in the cognitive processing. Fortunately, the AR material is designed based on the CTML, and many researchers have studied how to measure its cognitive activity. Eye tracking, combined with measures of learning performance, provides information about the focus of cognitive activity [31]. Consequently, to identify how learners behave in AR-based and other conventional learning environments, the use of an eye-tracking device is an effective way to provide cognitive processing measures.

Eye-tracking techniques can be utilized to record eye movement which can show how people behave while they are engaged in cognitive processing such as fixation count, total fixation time, and average fixation duration [32, 33]. However, the use and interpretation of eye-tracking measures are different and depend on research questions.

Table 1: Overview of experimental studies on AR for teaching and learning.

Reference	Domain	Setting	Participants	AR treatment	Control group treatment	Evaluation content
[24]	Biology	Classroom	72 fifth-grade children	AR graphic book	A picture book or physical interactions	Error; retention; satisfaction
[26]	Anatomy	Classroom	171 students: 78 with medicine degree, 48 with physiotherapy degree, and 45 with podiatry degree	AR software	Notes; videos	Acquisition of anatomy contents
[28]	Chinese writing	Classroom and field	30 12th grade students	AR-based writing support system	Text-graph writing support materials	Writing performance (subject, content control, article structure, and wording)
[21]	Mathematics	Field experiment	101 participants: 40 from primary school, 34 from secondary school, and 27 from university	AR mobile application	Physical information	Knowledge retention
[29]	Physics	Classroom	64 high-school students	AR-learning application	An educational website	Knowledge acquisition; flow experience
[30]	Architecture	Classroom	57 university students	AR mobile application	Text-graph materials	Academic performance
[23]	Natural science	Field experiment	57 4th grade students	AR-based mobile learning approach	Inquiry-based mobile learning approach	Learning achievement and motivation

Table 2: Overview of multimedia learning and cognition studies with eye tracking.

Reference	Materials	Eye tracker	Eye-movement metrics
[38]	Construction scenario images	EyeLink II	Fixation count; run count; dwell-time percentage
[39]	Construction site images	EyeLink II	First fixation time; dwell percentage; run count
[40]	Virtual building construction site	ViewPoint EyeTracker GIG160	Fixation count; scan path
[41]	Construction site	Tobii Pro Glasses2	Visit count; fixation count; total dwell time; time to the first fixation
[42]	Static (text and picture) and dynamic(text and video) recipe	FaceLab 4.6	Total fixation count; total fixation time; interscanning count
[43]	Web-based multimedia package	SMI iView X 2.4	Total fixation count; gaze sequence; dwell time in AOI (area of interest)
[44]	Images and texts with and without coloring	Tobii X60	Time to the first fixation; fixation numbers to the first fixation; total fixation count; fixation count percent
[45]	A digital learning environment with and without visual cues	Tobii T60	Total fixation time
[46]	Webpage	SMI iView X	Fixation duration; fixation count
[47]	Webpage	FaceLab 4	Total fixation count; fixation duration; average fixation duration; scan path
[48]	Text and picture	ASL 504	Total fixation time; transition count
[37]	Color-coded and conventional format of multimedia instruction	Tobii 1750	Average fixation duration; total fixation time; first fixation time

A summary of relevant studies in which eye tracking was used to conduct eye-movement measures in multimedia learning and cognition is listed in Table 2. Fixation duration and fixation count are the most prevalently used eye-tracking measures [34]. Generally, for the learning process, both longer fixation duration and lower fixation rates indicate higher cognitive load, and more fixation counts mean less efficient information processing. Moreover, a long average fixation duration means that deeper information processing is led by the complexity of the background information [32, 35, 36]. Besides, the attentional guidance hypothesis proposes that participants pay more attention to salient elements than other elements, which leads to longer fixation times [37].

In summary, three eye-movement measures, including total fixation time, fixation count, and average fixation duration are utilized in this study to demonstrate how learners behaved during the entire formal experimental process for the following reasons: (1) The higher the values of fixation count and fixation time, the more the cognitive load

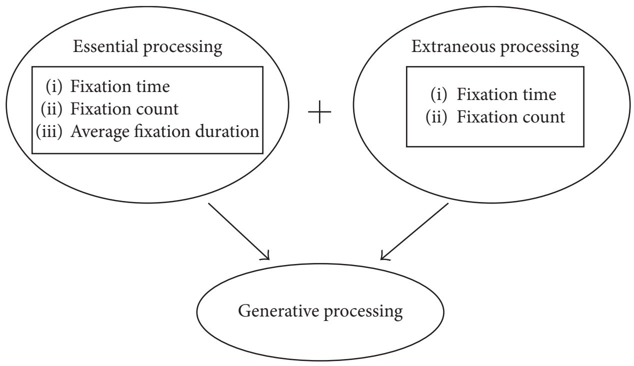


FIGURE 1: Relationship between the eye-movement metrics and the CTML cognitive processing.

in extraneous processing and the more the distributions in essential processing. (2) The longer the average fixation duration, the deeper the comprehension of the learning material, the more the complex information generated by various information sources, and the more the focus on essential processing. The relationship between the eye-movement metrics and the CTML cognitive processing is shown in Figure 1.

3. Research Questions and Methodology

The literature review shows that many related studies explain the effects of AR by comparing AR-based and TG-based (Table 1). These studies demonstrate the effectiveness of AR. However, they do not reveal the gap with PM-based education, which is also a common teaching method in construction education. The differences in effectiveness between AR and PM need to be examined to leverage the application of AR. Therefore, it is necessary to compare AR-based to TG-based and PM-based to provide convincing evidence with which to explore the effects of AR. On the contrary, although it has been proven that AR has a positive effect on learning outcomes, there is a lack of research works on the exploration and evaluation of AR in the cognitive process. Consequently, the researcher aims to prove the following hypotheses:

(1) Compared to TG- and PM-based materials, AR-based materials promote learning outcomes.

(2) Compared to the use of TG-based materials and PM-based materials, the use of AR-based materials that are designed using the CTML can lower learners' cognitive loads and foster deep information processing, which means that AR-based groups will have lower fixation counts and fixation times but higher levels of average fixation duration than TG- and PM-based groups.

To achieve the results, an experiment that involved learning and testing was developed. There were three groups of people who were exposed to three different learning environments: TG-based, AR-based, and PM-based learning environments. Each participant was separately given the same questions. The questions were answered by referring to the learning material provided in the TG-based, AR-based, or PM-based learning environments.

Figure 2 shows the experimental flow. Before the test, learning content and corresponding test questions were prepared. We randomly divided participants into the three groups (AR, TG, and PM). In the cognitive testing process, we recorded the participants' answers and answer times as their learning outcomes to comparatively analyze the three groups. During the whole testing process, participants' eye movements were recorded using an eye tracker (SMI iView XTM HED at 50 Hz). The fixation time and fixation count data were obtained using Begaze (iView software). We defined one area of interest (AOI) for each question, and total fixation time, fixation count, and average fixation duration values for each AOI were recorded and calculated.

3.1. Participants. A total of 40 senior undergraduate students majoring in construction management at Chongqing University were invited to participate. Because the samples of eye-tracking-related studies range from less than ten samples for qualitative studies to 30 for quantitative studies [49], a total of 40 samples are robust enough for a quantitative eye-tracking study.

Chongqing University is one of the top 10 research universities in the field of construction management in China. In this study, we use two approaches to invite participants: (1) students of one class were assigned to participate in the study as their final project; (2) an invitation flyer was posted in the laboratory of Chongqing University to invite volunteers to participate in the experiment. Finally, we selected 23 students from the class and 17 volunteers who were attracted by the flyer. To maximally avoid the differences between individuals, we choose participants with the same major (construction management), same grade (forth year), and similar age (21 to 23 years). There were 22 males and 18 females among the participants, and they all took the same courses in college. The students were trained with 32 credit hours of reinforcement arrangement courses in the third year of college, but they all lacked practical experience in construction, meaning that they did not receive any on-site training or have any injury experience in construction. Based on their academic and practical backgrounds, we assumed that these students had similar intrinsic learning abilities. The vision of all participants was either normal or corrected-to-normal.

3.2. Learning and Test Materials. Learning materials were about the detailing of longitudinal bars at the tops of antiseismic corner columns from one Chinese Drawing Collection for National Building Standard Design, 11G101-1 (drawing rules and standard detailing drawings of an ichnographic representing method for construction drawings of RC structure). According to our previous research and interviews with experts with engineering and construction majors in Chongqing University, this is quite an important and basic section of professional knowledge for construction workers. Meanwhile, it is difficult to understand for students who do not have any practical experience. Therefore, we

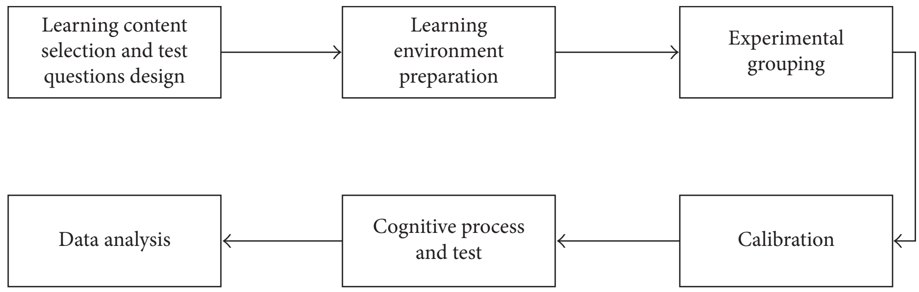
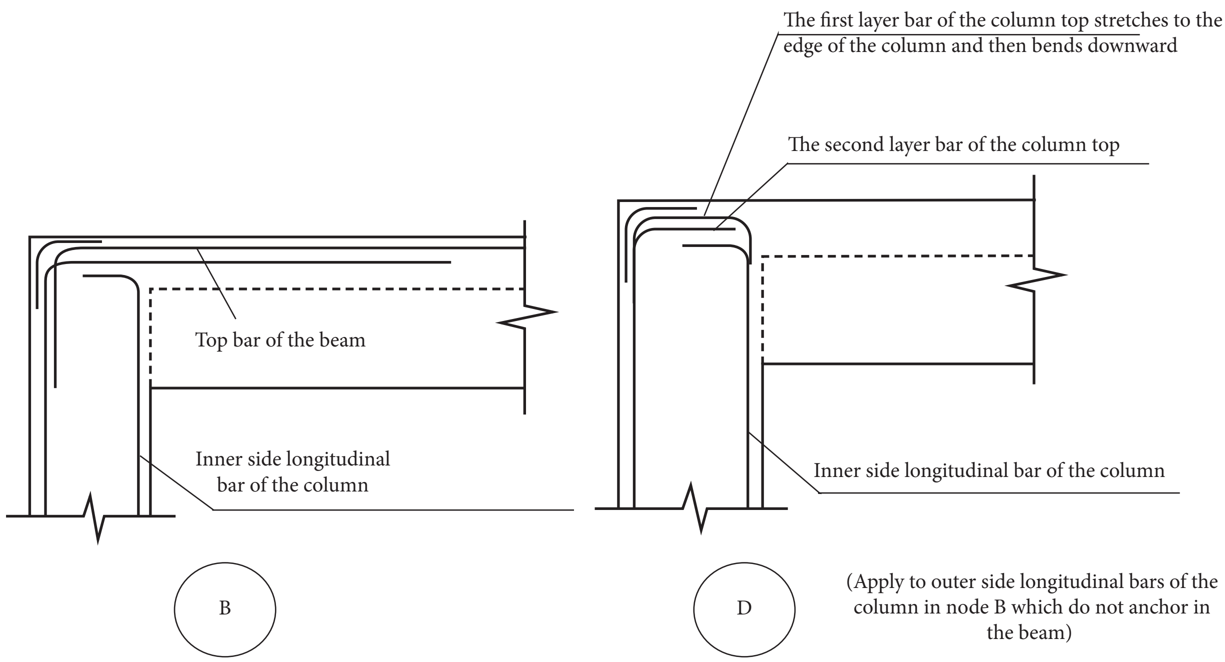


Figure 2: Experimental flow.



*Chinese characters were used in the formal experiment.

Figure 3: Paper-based learning material.

designed three forms of instructional materials based on this content with the guidance of a teacher in the field of construction techniques.

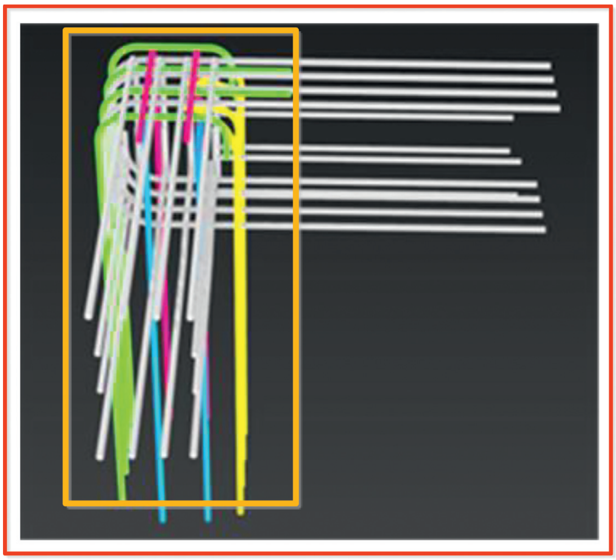
For the TG-based learning environment, the learning material was abstracted from 11G101-1 (Figure 3) and shown on a computer screen for learners.

Figure 4 shows the design of the AR model. The key steel bars are highlighted and distinguished based on their binding methods with various colors. The others are processed with gray to reduce its recognition. Thus, according to multimedia theory, this design could attract attention and help learners reduce extraneous processing. Besides, the key information can be easily selected to manage the essential processing and learners should have a better comprehensive understanding of learning contents with more effective generative processing. If one adopts the CTML, it can be supposed that AR-based learning environments may be more attractive than others, helping learners pay attention to key information.

The AR-based learning environment consisted of a computer with ARToolkit software, a camera, and a paper label. As shown in Figure 4, before the experiment, a virtual model based on the learning content was made with two software programs: Revit Structure, and 3D Max. Then, the ARToolkit was used to connect the model to a paper label. In the learning process, utilizing a plug-in installed in ARToolkit, which was developed in our previous research, put the paper label in front of the camera. The AR model would then appear on the label. The users could observe the model from different angles by rotating the label. Figure 5 shows the workflow of the AR-based learning environment, and the final practical AR-based environment is shown in Figure 6.

As for the PM-based learning environment, a solid model was made with mini-steel bars based on the actual situation on construction site, as shown in Figure 7.

Correspondingly, a test was designed to evaluate learning outcomes within the three different environments, and the test consisted of six questions in total, which in detail, included three true or false and three short-answer questions (Table 3). During the testing process, both learning material and text material were given on the same screen. Learning material was on the left and text material was on the right, with one question on each page. As shown in Figure 8, a cross-sectional drawing was given in the test



(i) Red frame: essential processing, that is, selection of key information
(ii) Yellow frame: extraneous processing, that is, highlighting the key steel bars and distinguishing them by their binding ways with colors

Figure 4: Design of the model for the AR-based learning environment.

material, and the configuration of each numbered longitudinal bar was arranged using one of the various ways shown in learning materials. Learners could reference the learning materials based on the questions, and they were asked to figure out the arrangement of each bar and their spatial relationships to give the correct answers. For each question, there was one corresponding AOI in learning material that showed the most important information that learners need to notice and process.

When answering true or false questions, learners were asked to make a judgment about a description associated with the spatial configuration and then answer with "yes" or "no." For the short-answer questions, on the basis of each question, learners were required to give the correct number of the 12.

3.3. Experimental Procedure. Every participant was randomly assigned to one of three groups. Each participant was provided training materials in TG-based, AR-based, or PM-based form. Referring to these training materials, the participants sequentially answered predesigned questions. Details about the experimental procedure are listed as follows.

3.3.1. Preexperiment Calibration. Participants were told about the purpose of the experiment. Then, they were asked to identify their dominant eye using the facilitator's instrument so that participants could be fit with the eye tracker (SMI iView XTM HED) with the proper eyeglass—with a sampling rate of 200 Hz. Participants were seated approximately 50 cm away from the front of the screen in which the learning materials were demonstrated. A five-point calibration screen was used to assess the calibration for each participant before each cognitive process. If the accuracy exceeded 1° in the x or y direction, then the calibration was repeated.

3.3.2. Formal Experiment. Every participant was given two minutes to familiarize themselves with the learning content. Six questions were then sequentially demonstrated on the screen (Figure 9). After the participant answered, the research facilitator immediately switched slides to the next question and recorded the participant's answer. No auxiliary verbal instructions were provided during the entire formal experiment in any group.

During the whole process, participants in the AR and PM groups could ask the research facilitator to rotate the paper label or model according to their own requirements if they wanted to observe from different angles. They were not given opportunities to change their answers.

3.4. Data Analysis. Every participant's answers and the completion times for every single question were recorded by the facilitator, and learners' eye movements were recorded by the eye tracker (SMI iView XTM HED) and the associated software (Begaze), which was utilized to build AOI. The total fixation time and fixation count of each AOI could be then calculated and exported.

Table 4 gives a brief definition of each measure. All data were imported into Excel and SPSS for statistical analysis. To identify if there were statistically significant differences among three groups, ANOVA was used to conduct group comparisons. If statistically significant results existed, then further Bonferroni multiple comparisons to identify the significant differences were conducted between the two groups.

4. Results

A total of 40 students participated in this study. However, because the eye-tracking data were missing for six participants, we finally had 34 subjects for analysis in this study, 11 for the TG group, 11 for the AR group, and 12 for the PM group. Thus, 204 ($34 * 6 = 204$) data points for each index were recorded or calculated. Before mathematical calculation was conducted, all data were checked with SPSS to identify outliers, and the result showed that five completion time data points, eight fixation time data points, six fixation count data points, and three average fixation duration data points were thought of as outliers and excluded during the following statistical analysis.

4.1. Learning Outcomes. As seen in Table 5, generally, the mean scores of the PM group were the highest, with minimum average completion times for both question forms. A significant difference of scores in short-answer questions ($p < 0.05$) was found among three groups, and multiple comparisons (Table 6) showed that the AR group and the PM group scored significantly higher than the TG group on the short-answer questions. No significant differences in

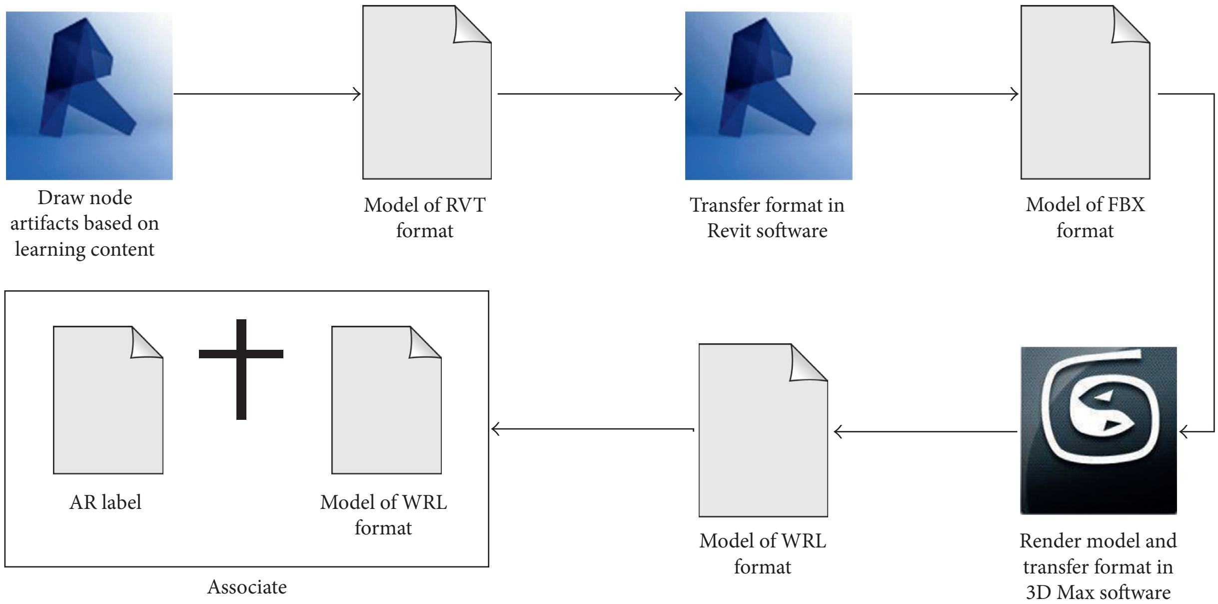


Figure 5: The workflow of AR-based learning environment preparation.

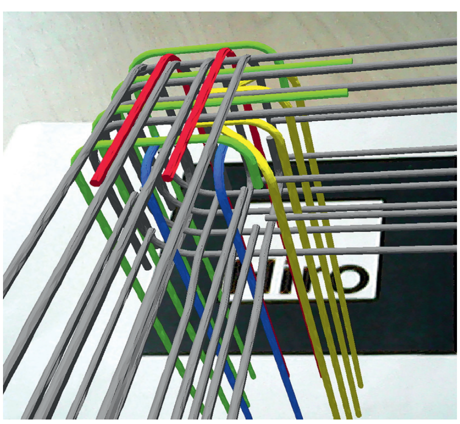


Figure 6: AR-based learning material.

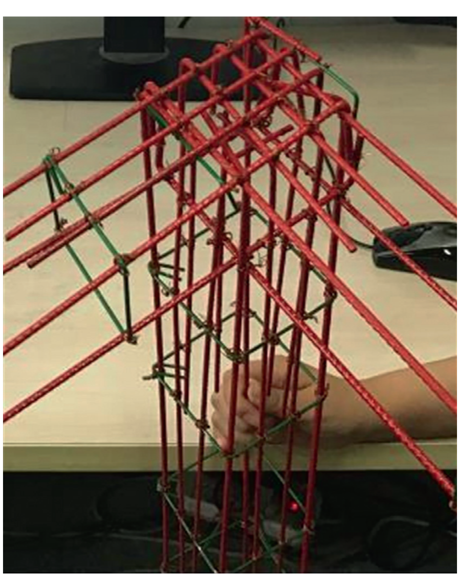


Figure 7: PM-based learning material.

Table 3: Test questions.

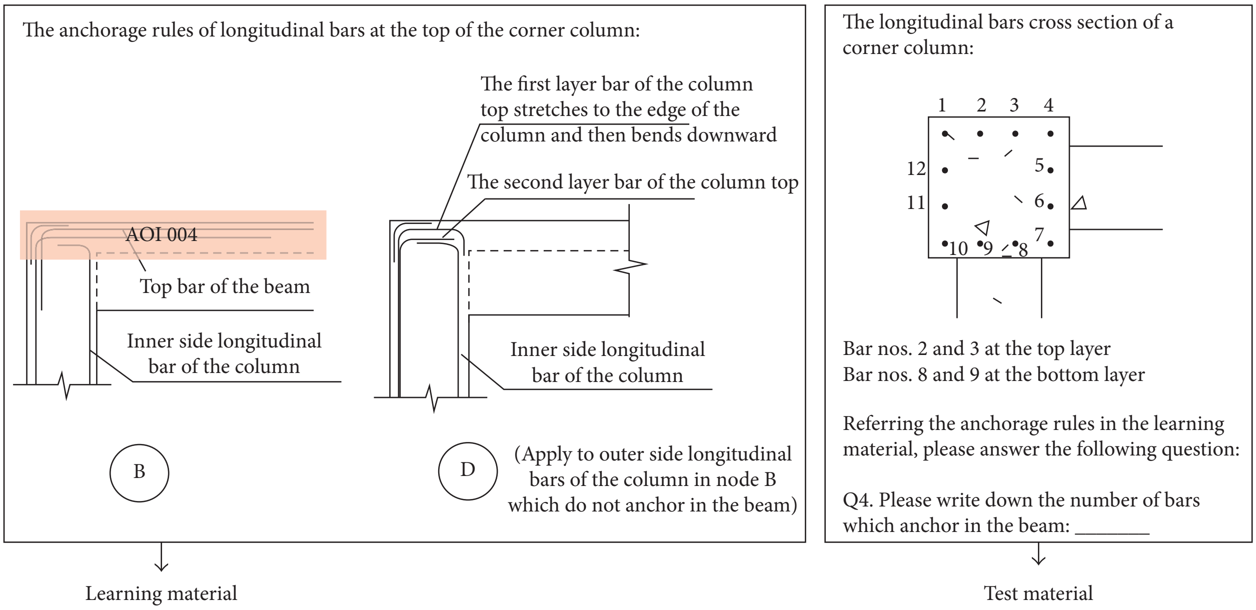
Question type	Question
True or false	(1) Do the longitudinal bars distribute in four layers in the node?
	(2) Does the no. 10 bar located in the second layer?
	(3) Do no. 1 and no. 12 bars anchor in the same way?
Short answer	(4) Please write down the number of bars which anchor in the beam.
	(5) Please write down the number of bars which anchor in the way of "bending towards the inside the column."
	(6) Please write down the number of bars which anchor in the way of "stretching to the edge of the column, then bending downward."

scores among the three groups were found in the true or false questions. There were no significant completion time differences among the three groups for either form of question.

People in the AR and PM groups performed better than those in the TG group. The increase in scores was much more significant for the short-answer questions. Contradictory to the first hypothesis, our findings showed that people in the PM group exhibited the same degree of learning performance as those in the AR group.

4.2. Eye-Tracking Measures. The eye-movement data were analyzed using ANOVA to explore learners' cognitive processes with regard to key information in AOIs.

Tables 7 and 8 show that for fixation time, people in the TG group spent significantly more fixation time on AOI compared to those in the PM group for true or false questions, and there were no significant differences regarding other comparisons between the two groups. The results of fixation count show that for true or false questions, people in the TG



*Chinese characters were used in the formal experiment.

Figure 8: Test interface.

Figure 9: Formal experiment.

group significantly fixed AOI more frequently than the other two groups. However, the result was different for the short-answer questions. Multiple comparisons showed that there were no significant differences between any two groups.

The average fixation duration result showed that significant differences were found in both question forms among three groups. Multiple comparisons determined that for true or false questions, people in the AR group showed a significantly higher level of average fixation duration than those in the TG group. For the short-answer questions, people in both the AR and PM groups showed a significantly higher level of average fixation time than those in the TG group.

The result of all eye-movement measures showed that AR-based learning material did not reduce learners' fixation counts or fixation times in all conditions. Moreover, no significant difference between AR-based and PM-based learning material was identified. People in the TG group spent significantly less fixation time on the true or false questions than those in the PM and AR groups, which could not fully prove the second experiment hypothesis.

However, the results demonstrate that the effects of AR and PM teaching were different for the two question forms. Although people in the TG group had similar scores on the true or false questions as people in the other two groups (Table 5), they had significantly longer fixation times and fixation counts. Long fixation times indicate that difficulty was faced in extracting information or that the object is more engaging in some way. Moreover, a high fixation count on AOI indicates inefficiency in identifying relevant information [34, 36, 50]. For the same learning outcomes, the result demonstrated that compared to the TG-based environment, both the AR-based and PM-based environments reduced learners' cognitive load sand improved their searching efficiency in the learning and test processes.

For the short-answer questions, people in the TG-based group exhibited the same level of fixation time and fixation count as those in the other two groups. However, it should be noticed that on the short-answer questions, participants in the AR and PM groups scored significantly higher than those in the TG group. Consequently, both AR-based and PM-based teaching considerably improved learners' answering accuracy, but it cannot be determined that which environment means lower cognitive load and searching efficiency by comparing eye-tracking data.

Table 4: Definition of measures used in this study.

Measures	Definition
Test score	The score of learners' answers; one point for each right answer
Completion time (s)	Total time spent on answering questions
Total fixation time (ms)	Total time fixated on an AOI
Total fixation count (time)	Total number of fixations counted within an AOI
Average fixation duration (ms)	Average duration of time of every fixation count on an AOI: the ratio of total fixation time and total fixation count

Table 5: Descriptive statistics of score and completion time.

Item	Question form	TG-based		AR-based		PM-based		F
		Mean	SD	Mean	SD	Mean	SD	
Score	True or false	0.52	0.51	0.67	0.48	0.72	0.45	1.70
	Short answer	0.06	0.24	0.61	0.5	0.67	0.48	20.90*
Completion time (s)	True or false	30.81	16.96	26.61	11.62	23.19	14.93	2.32
	Short answer	36.91	26.09	39.76	20.74	34.09	24.38	0.48

*The mean difference is significant at the 0.05 level.

Table 6: Multiple comparisons of items with significant differences.

Item	TG- and AR-based		TG- and PM-based		AR- and PM-based	
	Mean difference	Sig.	Mean difference	Sig.	Mean difference	Sig.
Score of short-answer questions	−0.55*	0.000	−0.61*	0.000	−0.06	1.00

*The mean difference is significant at the 0.05 level.

Table 7: Descriptive statistics of score and completion time.

Item	Question form	TG-based		AR-based		PM-based		F
		Mean	SD	Mean	SD	Mean	SD	
Fixation time (ms)	True or false	9.95	8.03	7.38	7.73	5.21	6.58	3.28*
	Short answer	5.35	7.61	9.97	9.69	10.21	9.17	3.17*
Fixation count (time)	True or false	21.68	20.55	8.79	8.28	7.36	8.28	11.27**
	Short answer	10.00	13.50	13.18	11.38	15.24	13.30	1.43
Average fixation duration (ms)	True or false	0.55	0.17	0.84	0.45	0.64	0.36	5.82**
	Short answer	0.41	0.23	0.69	0.28	0.66	0.27	10.87**

Note. $^{**}p < 0.01$; $^{*}p < 0.05$.

Unlike the two indicators of fixation time and fixation count, the result of average fixation duration showed that for both question types, the AR-based group had the highest level while the TG-based group had the lowest (Table 6). A long average fixation duration is thought to be an indication of deep processing [32]. When related information is easy to target and integrate, learners can likely engage in the deep processing of key information required for meaningful learning [37, 51, 52]. This result indicates that the AR-based learning environment helped learners more easily find and focus on key information for each question, which then lead to deep understanding of the content.

5. Discussion

The main purpose of the study is to understand how AR-based teaching impacts college students' learning outcomes and learning processes compared to TG-based and PM-based teaching about construction. The result showed that AR-based environments lead to better learning outcomes than TG-based environments, but not compared to PM-based environments. However, the difference on eye-tracking data did not keep the same gap during the whole process.

5.1. Effect of Question Form. Participants in the TG group scored significantly lower on the short-answer questions than those in the AR and PM groups. People in the three groups had similar scores for the true or false questions. In this study, to answer the true or false questions, learners just had to say "yes" or "no." However, they had given precise and comprehensive numbers of steel bars in the short-answer questions, which required more exact information processing. This result suggests that for some limited tasks, learners with TG-based learning or training environments can achieve ideal performance, despite the high cognitive load and inefficiency of doing so compared to when it is done in AR-based and PM-based environments. Moreover, TG-based teaching has the advantages of low cost and easy implementation. Therefore, for some learning tasks and practical work, TG-based education is the most economical option.

Table 8: Multiple comparisons of items with significant differences.

Item	Question form	TG- and AR-based		TG- and PM-based		AR- and PM-based	
		Mean difference	Sig.	Mean difference	Sig.	Mean difference	Sig.
Fixation time (ms)	True or false	2.57	0.532	4.74*	0.036	2.17	0.681
	Short answer	−4.62	0.111	−4.86	0.082	−0.24	1.000
Fixation count (time)	True or false	12.89*	0.001	14.32*	0.000	1.43	1.000
Average fixation duration (ms)	True or false	−0.29*	0.004	−0.10	0.940	0.20	0.061
	Short answer	−0.28*	0.000	−0.25*	0.001	0.03	1.000

*The mean difference is significant at the 0.05 level.

5.2. Effect of Cognitive Load and Emotion. Another reason why the participants in the TG-based group scored significantly worse on the second question form is related to cognitive load and motivation. As a positive emotion in cognitive processing, interest is closely related to motivation and attention, and those who with interest show greater persistence on subsequent tasks. Cognitive load may affect emotional state and further hamper effective visual search [53–55].

Before they started to learn, all learners in the three groups were thought to have positive emotions and motivations. Their performances at the beginning were based on the same emotion. In this study, the sequence of the test was three true or false questions followed by three short-answer questions. The TG-based group scored at the same level as the other two groups with significantly more fixations in the first three questions. We supposed that learners in the TG-based group experienced excessive cognitive load at the beginning, which further had a negative impact on their motivation, so they were not motivated enough to pay adequate attention to information processing. Thus, it led to the increasingly worse learning outcomes on the final three questions.

5.3. Effect of AR. Compared to the PM-based learning environment, the AR-based learning environment did not show a competitive advantage in learning performance or significant difference in eye-movement data with the exception of average fixation duration. The result showed that although the result of longer average fixation duration indicated that learners in the AR-based group more easily found and focused on key information and then had a better understanding of the learning content than others, this did not translate into superior learning outcomes. After the experiment, a few students were invited to experience all three learning tools. They generally thought that compared to the traditional TG-based learning method, both AR and PM are obviously helpful for them to understand the learning material. However, they did not indicate that there were significant differences between the effects of AR and PM. Their subjective is in agreement with our experimental result. It further indicates that the features and advantages of AR were not sufficiently utilized.

In practical application, AR has superiority in flexibility and convenience. In contrast to PM-based education, users can build AR-based learning or training environments with no limit on time, and the displayed objects can be repeatedly modified and utilized. Thus, AR has great potential and prospects. However, efficiently utilizing the features of AR to help learners or trainers achieve improved performance is not only the key to maximize its value but also the most persuasive reason for its application, which calls for further studies. It is worth exploring for which tasks AR is the most suitable environment or whether other ways need to be combined with AR to improve teaching and training efficiency.

6. Conclusion

In this study, we applied TG-based, AR-based, and PM-based learning environments for construction learning. We compared learners' learning outcomes and utilized eye tracking to explore the cognitive processes of the three groups.

For learning outcomes, our research suggests that the effects of learning environments are different for various forms of tasks. The three-dimensional display should have the advantage of showing objects more comprehensive and intuitively than other displays, but our study showed that, in terms of outcome, conventional TG-based training ways can achieve the same degree of AR-based and PM-based in some specific tasks, such as answering true or false questions. In practical application, the content and demand for learning and training are diverse for different majors and posts. AR and PM are not as effective in all cases. One should be careful and selective on the application and popularization of the new method.

Eye-tracking data provided quantitative evidence about the cognitive process. Both AR-based and PM-based environments helped learners reduce their cognitive loads compared to those in the TG-based group. However, lower cognitive loads did not transform into significantly higher test scores or quicker completion times compared to other groups. Similarly, eye-tracking data showed that AR has the potential for learners' key information focus and deeper understanding, but learners in the AR-based group did not show better learning performance than those in the other groups. This result suggests that to achieve improved outcomes, maybe we should combine other materials, such as 2D drawings and text, or perform more reasonable adjustments when modeling. To explore how to take full advantage of AR or other similar technology in practical application, additional research needs to be developed and integrated to provide an in-depth understanding of learners' mental models and cognitive processes.

In summary, this study illustrates the effects of TG-based, AR-based, and PM-based environments on construction learning outcomes and learners' cognitive processes. However, it remains limited by learning the single material and a few independent test questions. Future researchers should apply AR to systematized tasks and perform comprehensive tests to evaluate the effects of doing so.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Resource Unconstrained and Constrained Project Scheduling Problems and Practices in a Multiproject Environment

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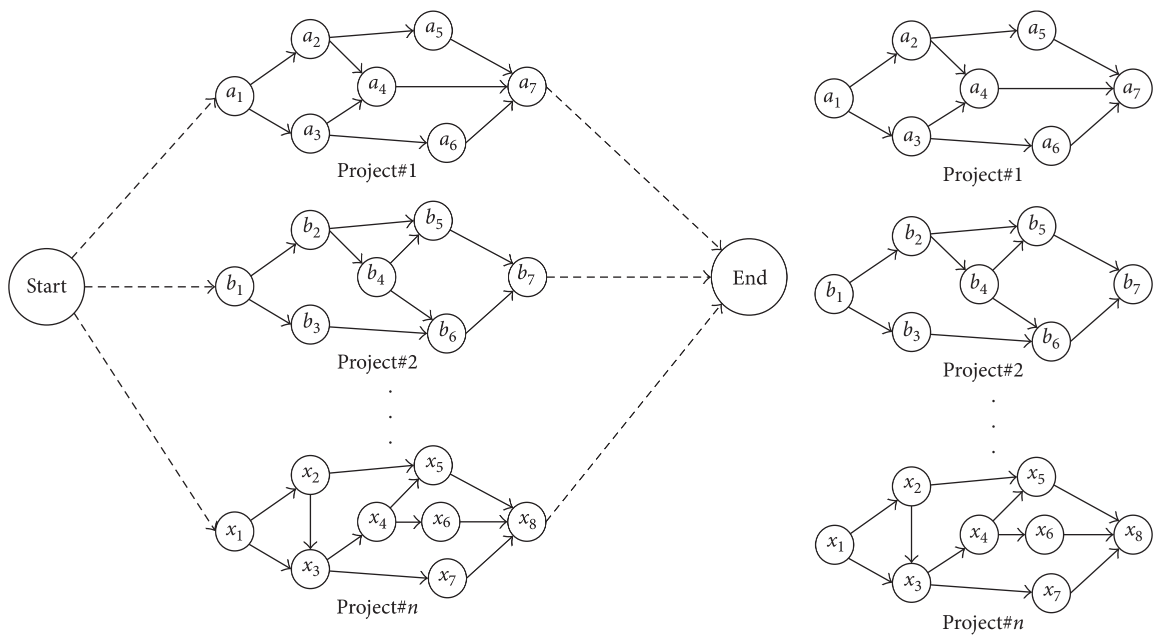
Construction companies execute many projects simultaneously. In such situations, the performance of one project may influence the others positively or negatively. Construction professionals face difficulties in managing multiple projects in limited resource situations. The purpose of this study is to identify the problems in multiproject scheduling from the practitioner's perspective and to discover current practices under resource unconstrained and constrained settings. The specific objectives are (1) determining the most challenging issues being faced in handling multiproject environment, (2) enumerating the practices adopted in the industry, and finally (3) identifying the practitioners' perceptions on the multiproject scheduling aspects such as network modeling approaches; activity execution modes; concept of sharing, dedicating, and substituting resources; centralized and decentralized decision-making models; solution approaches; and tools and techniques. An online questionnaire survey was conducted to address the objectives above. The top challenging issues in managing multiproject environment are identified. Factor analysis identified the factors by grouping the variables (a) decision-related, (b) project environment-related, (c) project management-related, and (d) organization-related factors. Resource-unconstrained situation mainly faces the issue of underutilization and wastage of resources leading to lower profit realization. The following findings were identified to overcome the unconstrained resource situation such as identifying the work front, adopting pull planning approach, creating a common resource pool, and allotting it on a rental basis. On the contrary, resource-constrained situation faces the issues of prioritization of resources, coordination, communication, collaboration, quality issues, and rework. The findings suggest the strategies such as top-up via subcontracting, proactive pull planning, introducing buffers, training the culture of the organization towards better communication, coordination, and collaboration, to improve the reliability of achieving baseline project performances. Various multiproject aspects suggested for effective management. The identified problems, practices, and various multiproject aspects are expected to contribute better management of multiproject resource unconstrained and constrained project scheduling.

1. Introduction

Organizations in the construction industry execute a portfolio of projects under tight time and resource constraints [1]. However, construction management research is dominated by a single-project model [2]. The ability to manage multiple projects in the competitive environment becomes an essential competence [3]. The projects may vary in size, importance, and the skill required at various stages and still use the same pool of resources [4]. Multiproject scheduling is a fundamental problem for enterprises to reasonably allocate the limited resources to optimize the performance of the project [5]. Herroelen [6] states that even a small improvement in multiproject management will yield a significant benefit to the project management field. More than 90% of all international projects are executed in a multiproject environment [7], and 84% of firms handle such multiple projects in parallel [8]. Therefore, the identification of challenging issues in the multiproject environment is highly beneficial.



(a) (b)

Figure 1: Network modeling approaches in the multiproject environment (MPE). (a) Single-project approach. (b) Multiproject approach.

The resource-unconstrained project scheduling approach presents a solution to time-constrained projects. However, the realistic situation involves optimizing multiple conflicting objectives in a resource-constrained project scheduling environment. The resource-constrained project scheduling problem (RCPSP) presents an extension to the standard Critical Path Method (CPM) and Program Evaluation and Review Techniques (PERT) by including the availability of resources [9]. The resource-constrained multiproject scheduling problem (RCMPSP) [10] and multimode resource-constrained multiproject scheduling problem (MRCMPSP) [11, 12] are the extensions of RCPSPs. The identification of resource unconstrained and constrained project scheduling problems and practices may lead to better management of the multiproject environment.

Yang and Sum [13] proposed the dual-level management structure for managing multiple projects. Project managers are responsible for operating the project activities, whereas upper-level managers work at a more tactical level and are in charge of all the projects and project managers. Traditionally, the RCMPSPs are solved with the assumption of centralized decision making in which the resource allocation and scheduling decisions were made centrally in an integrated manner [14]. Centralized planning model requires complete information of all the projects so that a satisfactory plan can be obtained more quickly. Coordination and communication channels should be in a proactive mode for the effective implementation of the centralized model. In practice, the resource allocation and scheduling functions are performed in a decentralized manner. The decentralized model has advantages in coordination and fairness among multiple projects and is more realistic [15, 16].

This study aims to identify the main challenges in multiproject scheduling from the practitioner's perspective and to discover current practices in resource unconstrained and constrained settings. The remainder of the paper is organized as follows. Section 2 describes the relevant literature specific to challenges in managing the multiproject environment: resource unconstrained and constrained situations. Section 3 outlines the research methodology to achieve the objectives above, and Section 4 discusses the results of challenges in multiproject environment: resource unconstrained and constrained multiproject problems and practices, and various aspects of multiproject scheduling. Finally, Section 5 describes the concluding remarks and possible future research directions.

2. Studies on Multiproject Scheduling Environment

Two main approaches are followed in the network modeling of multiproject scheduling: single-project approach [17, 18]; and multiproject approach [19] (Figure 1). In single-project approach, all projects are considered together to form a single critical path with the objective to minimize the total makespan (TMS). The single-project approach has several drawbacks: (i) it is less realistic and implicitly assumes equal delay penalties and (ii) in many practical situations, each project has its manager who is interested in achieving the individual project's performances [19]. In, multiproject approach, each project is handled independently with the objective to minimize the average project delay (APD).

In multiproject scheduling, the projects are prioritized based on project selection priority rule [10]. Traditionally, all projects are controlled by one decision maker. Nowadays,

Table 1: Challenges in a multiproject environment (MPE).

	Challenges	Reference(s)
1	Division and assignment of resources/resource allocation	[2, 4, 9, 25–27]
2	Organizational culture	[26, 27]
3	Management support	[4]
4	Prioritization/project selection	[4, 25]
5	Real-time monitoring and proactive decision making	[23]
6	Capacity (resource)	[7, 24]
7	Complexity (multiple interfaces between the projects)	[2, 7]
8	Conflict (people, system, and firm issues)	[7]
9	Commitment	[4, 7, 24]
10	Context (regulative, normative, and cognitive)	[7, 9, 24]
11	Communication	[4, 25]
12	Coordination	[24]
13	Volatile economic environment	[2]
14	Dynamic nature	[24]
15	Duration and resources (cascade effect)	[24]
16	Competencies of project manager	[4, 25–27]
17	Project manager assignment	[27]
18	Project management processes (information sharing)	[25, 27]

due to active intrafirm and interfirm collaborations, multiproject management has entered a new environment where different self-interested decision makers control the projects. It seems that centralized RCMPSP is no more valid for the current situation. Under this background, the decentralized RCMPSP is formally proposed [20, 21]. The attributes of decentralized/distributed (multiagent) multiproject scheduling problem are the decision maker, the decision mode, and the coordination approach. Coordination is achieved through centrally imposed solutions, contracts, auction, argumentation, and mediated single-text negotiations [22]. The applicability of decision-making models needs to be evaluated from the practitioner's perspective.

2.1. Challenges in a Multiproject Environment. In a multiproject environment, organizations expect (1) structured approach for making "go" or "no-go" decisions during project selection, (2) looking for an optimum program schedule that incorporates significant decision variables of the company, project delivery system, individual project objectives, driven factor, and priority, (3) dealing with uncertainties, and (4) real-time monitoring of the projects [23–27]. Table 1 identifies the common challenges in the multiproject environment (MPE).

2.2. Resource-Unconstrained Multiproject Scheduling. Most widely used CPM and PERT techniques deal with time aspect only [28]. It has severe limitations: (1) assumes unlimited resources and (2) applies to only one project at a time [29–31]. Besides, Fondahl [32] introduced the precedence diagramming method (PDM) to represent a realistic relationship between the activities. However, the inability to perform resource scheduling is the main drawback of the network scheduling methods. CPM, PERT, and PDM methods fail to synchronize activity planning and resource planning seamlessly. Neither Gantt nor CPM, PERT, and PDM address the decisions required in multiproject setting [33]. Although these models are still applicable in some real-world projects, a deterministic assumption and limited to single-project application make it inaccurate for multiproject environments. In multiproject environment, resources are constrained, but the aforementioned methods did not cover this situation. Hence, the resource-constrained multiproject scheduling consideration is essential [34].

2.3. Resource-Constrained Multiproject Scheduling. Typically, multiple projects share common resource pools whose capacities are not sufficient to support all project activities at the same time, leading to the resource-constrained multiproject scheduling problem (RCMPSP) and multimode resource-constrained multiproject scheduling problem (MRCMPSP) [35]. MRCMPSP is the extension of RCMPSP where each activity possesses different execution modes. The activities can be executed with the several combinations of modes using various construction methods, materials, crew size, and overtime policy. Under this situation, each combination will have different project performances regarding time, cost, and quality [5]. Although RCMPSP and MRCMPSP play a vital role in project management, there are not many fruits on the topic. The main reason is due to high complexity, which is affected by many factors, such as the vast solution space, the intensity contending for resources, conflicting objectives, the interproject dependency and priority, and the high level of uncertainty [36, 37].

The multiproject intention is to prioritize the project's activities to optimize an objective function without violating both intraproject and interproject resource constraints. Choosing between alternative optima makes the changes in the scheduling easier and faster than rescheduling [38]. At the tactical planning level, managers face the crucial decisions such as allocating resources among various projects, establishing due dates and other milestones for bidding proposals, and determining the optimal trade-off between the absorption of resources and the duration and the costs associated with alternative "modes" of performing each activity. It should be noticed that such decisions have an enormous impact on the whole performance of a company [39].

Kim and Leachman [40] proposed linear programming to optimize the trade-offs of lateness costs among projects. Deckro et al. [41] offered the integer programming with decomposition approach for solving the multiproject, resource-constrained scheduling problem. Mittal and Kanda [42] considered integer linear programming model for interproject resource transfers. Krüger and Scholl [43] proposed a framework for resource transfers considering (i) managerial approaches—transfer neglecting approach, resource reducing approach, and resource using approach;

(ii) types of resource transfers—time, abstraction, and support. Confessore et al. [20] developed an iterative combinatorial auction mechanism for the agent coordination using dynamic programming. Liu and Wang [44] established a profit optimization model for multiproject scheduling problems considering cash flow and financial requirements. Exact methods suffer from large problems due to the combinatorial explosion phenomenon [45]. It is not computationally tractable for any real-life problem size, rendering them impractical [46, 47].

Another alternative is the approximate methods which can be divided into priority rule-based heuristics, classical metaheuristics, nonstandard metaheuristics such as agent-based, and different heuristics [48]. Kurtulus and Davis [49] proposed multiproject scheduling rules to minimize total project delay: shortest activity of shortest project (SASP), largest activity of largest project (LALP), activity with highest resource demand first (MAXRD), activity with maximum slack first (MAXSLK), activity with lowest precedent work, activity with highest precedent work. Lova and Tormos [8] analyzed the effect of priority rules, minimum late finish time (MINLFT), minimum slack (MINSLK), maximum total work content (MAXTWK), and SASP or first come first serve (FCFS) with network modeling approaches, and found that MINLFT with multiproject approach performed the best. MINLFT produces most substantial different best schedules almost equal to those produced by MINSLK and minimum late start time (MINLST) [50]. The maximum total work content (MAXTWK) can be more efficient with the bounds of resource usage in multiproject schedules [51]. Suresh et al. [10] analyzed the two-phase priority rules, that is, project priority rules and activity priority rules to maximize the net present value (NPV) under resource transfer times. Heuristic methods have been extensively used in practice [52]. However, heuristic models are problem-dependent, implies that the rules specific to a model cannot be applied equally to all problems [53], and do not guarantee an optimal solution.

The various neighborhood and population-based metaheuristics provide a generalized and robust approach to offset the limitations imposed by the exact and rule-based heuristics. Chen and Shahandashti [54] utilized simulated annealing (SA) for optimizing multiproject linear scheduling. Suresh et al. [10] presented genetic algorithm (GA) approach to the multiproject scheduling problem with resource transfer times. Tran et al. [55] introduced a fuzzy clustering chaotic-based differential evolution (DE) for solving multiple resources leveling in the multiple projects scheduling. Rokou et al. [56] implemented the GA to deal with classification and prioritization of the projects and ant colony optimization (ACO) to perform the activity list optimization for each project. Deng et al. [57] applied particle swarm optimization (PSO) to search the optimal schedule for the RCMPSP. A nondominated sorting genetic algorithm II (NSGA-II) is proposed to obtain optimal trade-offs between different projects objectives [5]. Abido and Elazouni [58] introduced strength Pareto evolutionary algorithm (SPEA) to minimize the financing costs, duration of a group of projects, and the required credit. Even though many approaches have been proposed to handle the multiproject environment, learning from practices still required to consider the integrated behavior of various multiproject modeling aspects. This study is proposed to identify the multiproject scheduling problems and practices with resource unconstrained and constrained settings from the practitioner's perspective.

3. Research Methodology

A questionnaire survey is adopted to identify resource unconstrained and constrained multiproject scheduling problems and practices. Constructivist ontology and positivist epistemology have been adopted as research philosophy along with quantitative and qualitative research methodology, survey research design, and questionnaire-based research method. A questionnaire-based study is applied predominately for descriptive research, seeking to investigate and analyze research problems [59].

3.1. Design of the Questionnaire Survey. The survey is done through an email-based questionnaire. The respondent contact information is obtained through LinkedIn. The survey consists of five parts: first, challenges faced in managing multiproject environment; second, resource-unconstrained problems and practices; third, resource-constrained problems and practices; fourth, various multiproject environment aspects such as network modeling approaches, decision-making models, activity execution modes, concepts of sharing, dedicating, and substituting resources, solution methods, and tools and techniques; and in the last part, the respondent demographics are collected. The first part of the survey consists of ordinal data related to importance scale 1 to 5 (Likert scale). Five-point Likert scale appears to be less confusing and increases the response rate. Previous authors have used a similar scale for the construction management research [26, 60]. In the second and third parts of the survey, the subjective opinions are extracted for the resource unconstrained and constrained situations, and each has three subitems. The fourth part of the survey involves nominal data and subjective opinions. The final part contains information such as respondent designation, years of experience, the category of stakeholder, and region.

3.2. Characteristics of Respondents. The pilot study was conducted to refine the survey questions from the three industry experts. The responses are collected from sample units project engineer, planning engineer, project manager, construction manager, and general manager. A total of 90 valid responses were received. The responses were received from 17 different countries: India, UAE, Oman, Saudi Arabia, Qatar, South Africa, USA, UK, Malaysia, Australia, Iran, Singapore, Peru, Bahrain, Russia, Sri Lanka, and Pakistan. The distribution and characteristics of the respondents were tabulated in Table 2.

Table 2: Demographics of respondents.

Demography	Project engineer	Planning engineer	Project manager	Construction manager	General manager	Total
Experience						
<5 years	15	10	2	0	0	27
5–10 years	1	8	10	8	0	27
>10 years	1	3	15	8	9	36
Stakeholder						
Client	0	2	1	1	5	9
Project management consultant	5	5	8	3	1	22
Main contractor	11	12	16	12	2	53
Subcontractor	1	2	2	0	1	6
Region						
India	12	8	8	7	5	40
UAE	0	2	3	3	0	8
Oman	0	3	1	3	0	7
Saudi Arabia	0	1	3	0	2	6
Qatar	2	2	1	0	0	5
Others (South Africa, USA, UK, Malaysia, Australia, Iran, Singapore, Peru, Bahrain, Russia, Sri Lanka, and Pakistan)	3	5	11	3	2	24
Total	17	21	27	16	9	90

3.3. Method of Data Analysis. The study was analyzed using SPSS V.24. The method of data analysis was as follows:

(1) Many previous researchers employed a relative importance index to rank the variables [60, 61]. The respondents are divided into two categories: (a) client and project management consultant (PMC) who monitors the project, and (b) main contractor and subcontractor who execute the project. The overall ranking is calculated from the combination of all stakeholders.

$$\text{Relative importance index (RII)} = \frac{\sum W}{A * N}, \quad (1)$$

where W is the weight given to each variable by the respondents, which ranges from 1 (least important), 2 (fairly important), 3 (important), 4 (very important), to 5 (most important); A is the highest weight of variable (i.e., 5); and N is the total number of respondents.

Spearman rank correlation coefficient is applied to measure the strength of the monotonic relationship between pairs of variables that influence the performance of multiproject environment. Correlation coefficients 0–0.19, 0.2–0.39, 0.4–0.59, 0.6–0.79, and 0.8–1 are considered to very weak, weak, moderate, strong, and very strong relationship, respectively, between the variables [62].

Kruskal–Wallis test is a nonparametric test alternative to one-way ANOVA for testing whether samples originate from the same distribution. The authors check the distribution between the stakeholder categories such as (a) client and project management consultant, and (b) main contractor and subcontractor.

Null hypothesis H0: significant difference does not exist in the distribution of multiproject environment variables among the stakeholder category.

Alternate hypothesis H1: significant difference exists in the distribution of multiproject environment variables among the stakeholder category.

(2) Factor analysis is used to identify the common correlating variables to form a few underlying factors. Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of Sphericity are conducted to evaluate the adequacy of sample data. Initially, the eigenvalue is set to greater than 1 for extracting the factors. Once it is identified, then factor extraction limit is assigned. Orthogonal varimax is assigned to interpret the variables. Finally, the reliability (Cronbach alpha) test is conducted for each factor and all the variables [62].

(3) Chi-square goodness of fit is employed to find out if there is a statistically significant difference between an observed set of frequencies and an expected set of frequencies of various aspects of the multiproject environment: network modeling approaches, activity execution modes, decision-making models, and solutions methods.

Null hypothesis H0: significant difference does not exist between observed and expected frequencies of multiproject environment aspects.

Alternate hypothesis H1: significant difference exists between observed and expected frequencies of multiproject environment aspects.

(4) Qualitative analysis: examining each line of data and then defining actions within (open), making connections between a category and its subcategory (axial), identifying the frequently reappeared core variables (selective). The following questions are addressed: (a) what can be learned from resource unconstrained and constrained situations? and (b) how various resource-constrained multiproject scheduling aspects are perceived?

Table 3: Ranking of challenges in managing the multiproject environment (MPE).

Variables	Client and project management consultant Rank (RII)	Main contractor and subcontractor Rank (RII)	Overall ranking Rank (RII)
1. Division and assignment of resources/resource allocation	7 (0.813)	1 (0.881)	2 (0.858)
2. Organizational culture	12 (0.690)	10 (0.753)	12 (0.731)
3. Management support	2 (0.845)	9 (0.776)	7 (0.800)
4. Prioritization/project selection	8 (0.787)	12 (0.742)	11 (0.758)
5. Real-time monitoring and proactive decision making	5 (0.832)	2 (0.878)	1 (0.862)
6. Capacity	13 (0.690)	13 (0.692)	13 (0.691)
7. Complexity	14 (0.690)	14 (0.681)	14 (0.684)
8. Conflict	18 (0.587)	15 (0.671)	15 (0.642)
9. Commitment	9 (0.781)	11 (0.753)	10 (0.762)
10. Context	15 (0.639)	18 (0.614)	18 (0.622)
11. Communication	6 (0.832)	5 (0.854)	5 (0.847)
12. Coordination	4 (0.839)	3 (0.858)	4 (0.851)
13. Volatile economic environment	17 (0.606)	16 (0.651)	17 (0.636)
14. Dynamic nature	16 (0.619)	17 (0.651)	16 (0.640)
15. Duration and resources (cascade effect)	10 (0.781)	8 (0.790)	9 (0.787)
16. Competencies of project manager	3 (0.845)	6 (0.844)	6 (0.844)
17. Project manager assignment	11 (0.768)	7 (0.803)	8 (0.791)
18. Project management processes (information sharing)	1 (0.852)	4 (0.858)	3 (0.856)

4. Results and Discussion

4.1. Ranking of Challenges in the Multiproject Environment (MPE). The relative importance index and ranking were calculated for each variable under two categories of stakeholders (Table 3). The top ranking challenges based on Client and PMC are project management processes (information sharing), management support, competencies of project manager, coordination, real-time monitoring and proactive decision making, and communication. The top ranking challenges based on main contractor and subcontractor are division and assignment of resources/resource allocation, real-time monitoring and proactive decision making, coordination, project management processes (information sharing), communication, and competencies of project manager. The five variables are shared among the two categories of stakeholders, whereas the final ranking considers the combined effect of all respondents that influence the performance of multiproject environment: (1) real-time monitoring and proactive decision making, (2) division and assignment of resources/resource allocation, (3) project management processes (information sharing), (4) coordination, (5) communication, and (6) competencies of project manager (Table 3).

Kruskal–Wallis test was applied to check whether a significant difference exists among the stakeholder's responses on the variables. The respondents were grouped into two categories: client-side (client and project management consultant) and contractor-side (main contractor and subcontractor). Statistically, a significant difference exists among the stakeholder categories only for the variables division and assignment of resources/resource allocation and management support. Management support variable is located in the seventh position considering the overall ranking, whereas a significant difference does not exist for the remaining 16 variables (Table 4).

The degree of correlation between the variables that influence the performance of multiproject environment was evaluated among one-third of the variables. Real-time monitoring and proactive decision making are moderately correlated with coordination and communication. Project management processes (information sharing) are also moderately correlated with competencies of project manager, coordination, and communication. A moderate correlation exists between the coordination and communication variables. However, the other relations between the variables are found to be weak and very weak (Figure 2). Coordination among project managers of different projects is paramount essential to achieve the efficient use of limited resources in the multiproject situation. Coordination is critical at the lower level to divide and assign the resources to meet operational efficiency. Coordination is also essential at the higher level for portfolio efficiency. The efficiency of a portfolio depends on individual projects' operational capabilities. For that, project manager's competency is the key.

4.2. Factor Analysis. The variables mentioned in Table 3 were considered for the factor analysis. The subject to item ratio was found to be 5 : 1 [63, 64]. KMO-test value of 0.824 confirmed the measure of sampling adequacy with the statistical significance of Bartlett's test of Sphericity. There are four factors recognized with the eigenvalue greater than 1. Scree plot also suggests the four components (Figure 3) [62]. Prioritization/project selection variable was removed

Table 4: Kruskal–Wallis test for checking the differences between client-side and contractor-side.

Result	Summary	
	Variable	χ^2 (1, N = 90)
Significant difference exists	1. Division and assignment of resources/resource allocation	5.108, $p < 0.05$
	3. Management support	4.303, $p < 0.05$
Significant difference does not exists	2. Organizational culture	3.565, $p > 0.05$
	4. Prioritization/project selection	1.573, $p > 0.05$
	5. Real-time monitoring and proactive decision making	1.425, $p > 0.05$
	6. Capacity	0.065, $p > 0.05$
	7. Complexity	0.003, $p > 0.05$
	8. Conflict	3.495, $p > 0.05$
	9. Commitment	0.499, $p > 0.05$
	10. Context	0.051, $p > 0.05$
	11. Communication	0.379, $p > 0.05$
	12. Coordination	0.674, $p > 0.05$
	13. Volatile economic environment	1.107, $p > 0.05$
	14. Dynamic nature	0.987, $p > 0.05$
	15. Duration and resources (cascade effect)	0.007, $p > 0.05$
	16. Competencies of project manager	0.039, $p > 0.05$
	17. Project manager assignment	0.911, $p > 0.05$
	18. Project management processes (information sharing)	0.057, $p > 0.05$

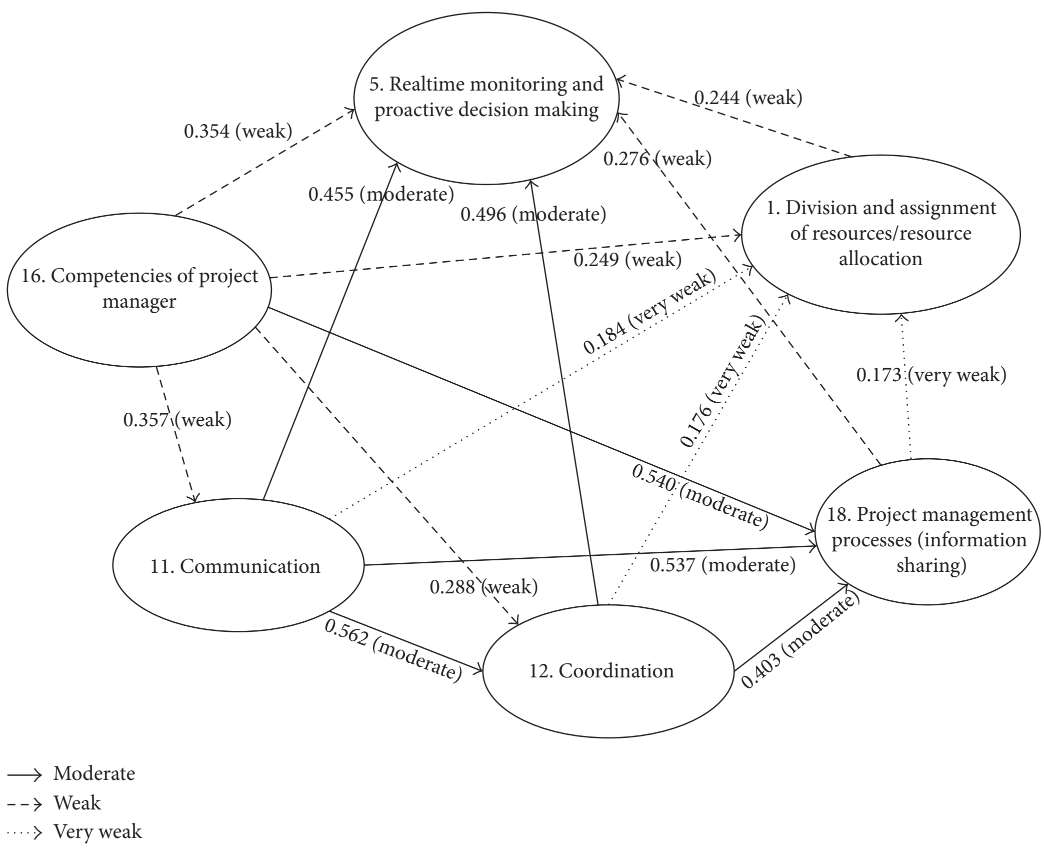


Figure 2: Spearman's rank correlation relations among the top six variables.

during the factor extraction. Factor 1 explains the total variance of 17.911% and contains six variables (Table 5). In Table 6, factor 1 variables have the Pearson correlation coefficient values between 0.284 and 0.575. The variables communication, coordination, conflict, real-time monitoring and proactive decision making, complexity, and capacity

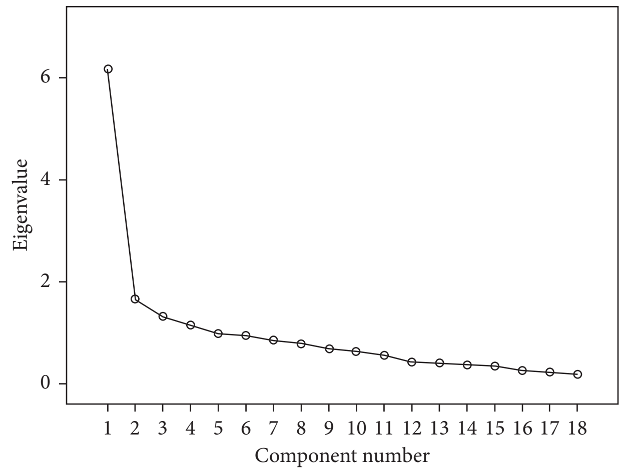


Figure 3: Scree plot.

Table 5: Factor analysis: factor loading and the percentage variance explained.

Name of the factor	Factor loading	% variance explained
Factor 1: decision-related		
11. Communication	0.725	17.911%
12. Coordination	0.698	—
8. Conflict	0.673	—
5. Real-time monitoring and proactive decision making	0.595	—
7. Complexity	0.520	—
6. Capacity	0.467	—
Factor 2: project environment-related		
14. Dynamic nature	0.748	15.613%
13. Volatile economic environment	0.702	—
10. Context	0.646	—
15. Duration and resources (cascade effect)	0.614	—
9. Commitment	0.538	—
Factor 3: project management-related		
17. Project manager assignment	0.861	14.107%
16. Competencies of project manager	0.828	—
18. Project management processes (information sharing)	0.635	—
1. Division and assignment of resources/resource allocation	0.431	—
Factor 4: organization-related		
3. Management support	0.767	9.543%
2. Organizational culture	0.748	—

Table 6: Pearson correlation coefficient matrix for the variables in factor 1.

Variables	11	12	8	5	7	6
11	1	—	—	—	—	—
12	0.575	1	—	—	—	—
8	0.390	0.370	1	—	—	—
5	0.512	0.549	0.277	1	—	—
7	0.417	0.284	0.406	0.376	1	—
6	0.475	0.353	0.288	0.307	0.465	1

empower the decision-making capabilities. Hence, factor 1 is labeled as decision-related. Factor 2 explains the total variance of 15.613% and comprises five variables (Table 5). In Table 7, factor 2 variables have the Pearson correlation coefficient values between 0.370 and 0.641. The variables' dynamic nature, volatile economic environment, context, duration and resources, and commitment to this factor concentrate on the project environment-related issues. Therefore, factor 2 is considered as project environment-related. Factor 3 explains the total variance of 14.107% and includes four variables (Table 5). In Table 8, factor 3 variables have the Pearson correlation coefficient values between 0.225 and 0.716. The variables project manager assignment, competencies of project manager, project management processes, and division and assignment of resources under this factor focus on the project management aspects. Thus, factor 3 is termed as project management-related. Factor 4

Table 7: Pearson correlation coefficient matrix for the variables in factor 2.

Variables	13	14	10	15	9
13	1	—	—	—	—
14	0.426	1	—	—	—
10	0.446	0.441	1	—	—
15	0.436	0.513	0.426	1	—
9	0.441	0.370	0.641	0.427	1

Table 8: Pearson correlation coefficient matrix for the variables in factor 3.

Variables	17	16	18	1
17	1	—	—	—
16	0.716	1	—	—
18	0.580	0.517	1	—
1	0.261	0.259	0.225	1

explains the total variance of 9.543% and contains two variables (Table 5). The value of Pearson correlation coefficient for the variables in factor 4 is 0.327. The variables management support and organizational culture focus on the organizational aspects. Hence, factor 4 is labeled as organization-related. Similar research studies have been found earlier; however, those [26, 27] are merely on the relative importance index.

Cronbach's alpha test was conducted for all variables as well as variables in each factor. The value of Cronbach's alpha lies in the range of 0 to 1; higher value indicates greater internal consistency and vice versa. C_α value higher than 0.7 is considered to be acceptable: the variables in factor 1 (0.793), the variables in factor 2 (0.806), the variables in factor 3 (0.757), and all variables (0.880). C_α value is unacceptable for the variables in factor 4 (0.486); the reason might be the existence of only two variables.

4.3. Resource-Unconstrained Multiproject Scheduling Problems and Practices. Resource-unconstrained situation exists in staff cadre only. The resources are set to be unconstrained only when the time is constrained. Resource-unconstrained projects face many difficulties: (a) optimal use of resources; (b) control of resource wastes; (c) lavish use of resources leads to cost overruns and profit loss; (d) underutilization of resources; and (e) lack of coordination, communication, and commitment. Resource-unconstrained projects can be efficiently handled through: (a) identifying the adequate work front; (b) multiple authorities for decision making; (c) reconciling the resource allocations at regular intervals (proactive resource planning); (d) optimization of resources by implementing real-time productivity tracking; (e) awareness of selection and deployment of resources to suit the budget, specification, and timeframe; (f) pull planning and restriction analysis before the start of task; (g) effective communication strategies with project heads on a regular basis for resource allocation; (h) creating common resource pool and charge the projects on rental basis; (i) key personnel should be trained to use management tools at all levels of project; and (j) migrate the minset towards resource-constrained schedules.

4.4. Resource-Constrained Multiproject Scheduling Problems and Practices. Resource-constrained projects face issues in (a) prioritization of resources based on experience and critical path identification; (b) lack of coordination, communication, and collaboration; (c) unskilled labor; (d) outdated machinery; (f) unqualified supervision; (g) quality issues; (h) reworks; and (i) awareness of using new technologies. Resource-constrained projects can be handled efficiently through: (a) increased supervision, (b) proper training, (c) top-up via subcontracting, (d) overtime works, (e) closely monitoring the productivity, (f) implementing lessons learnt from past experiences, (g) better coordination and extensive use of schedules, (h) use of competent project management tools, (i) proactive pull planning and monitoring on a regular basis, (j) introduction of buffers, (k) accountability on achieving the cycle time, (l) centralized database with active communication channel, (m) culture of the organization's need to train for cooperation, (n) alternative planning options in terms of whether to buy or hire the number of required resources, (o) automating the repetitive activities to eliminate the variances and improve the reliability, (p) incentives to retain the skilled workmen, and (q) crashing activities for resource smoothing.

4.5. The Various Aspects of the Multiproject Environment (MPE). The descriptive information of the various multiproject environment aspects was tabulated (Table 9). Chi-square goodness-of-fit test was performed to check whether the following multiproject environment aspects are equally preferred among the practitioners (Table 10). The multiproject approach is preferred over the single-project approach. The test confirmed that statistically, a significant difference exists. The reason is that in the multiproject approach, each project is considered independent of other projects to minimize the average project delay. Activities can be executed with the different combinations of construction methods, materials, and crew sizes. It is highly significant because the baseline planned resources may not be available during the actual construction. Therefore, variability in the duration of execution has to be minimized. The different activity execution modes can take various performances of time, cost, and quality. However, some of the activities have to be complete based on their baseline specifications because of contractual conditions. Therefore, single and multiple execution modes are required to complete all tasks in the project. There is a significant difference exists between single mode, multimode, and preferring both execution modes.

Centralized decision-making model is preferred for long duration projects whereas decentralized model is preferred for short duration projects. Centralized model is effective in controlling the progress throughout the project management process. Project value above INR 500 million is considered under the centralized model. To adopt the efficient centralized model, the information should flow from bottom to top and then top to bottom with active

Table 9: Descriptive information on the various aspects of the multiproject environment.

Aspects of the multiproject environment		Counts (n = 90)
1. Network modeling approach	(a) Single-project approach	16
	(b) Multiproject approach	74
2. Activity execution modes	(a) Single mode	16
	(b) Multimode	71
	(c) Both	3
3. Decision-making models	(a) Centralized	40
	(b) Decentralized	28
	(c) Both	22
4. Solution methods	(a) Exact	14
	(b) Heuristics	54
	(c) Metaheuristics	18
	(d) Not aware	4

Table 10: Chi-square goodness of fit for the various aspects of the multiproject environment.

Result	Summary	
	Aspects of the multiproject environment	Chi-square
Significant difference exists	Single-project and multiproject approach	χ^2 (1, N = 90) 37.38, $p < 0.05$
	Single, multiple, and both activity execution modes	χ^2 (2, N = 90) 86.87, $p < 0.05$
	Exact, heuristics, metaheuristics, and not aware	χ^2 (3, N = 90) 63.42, $p < 0.05$
Significant difference does not exists	Centralized, decentralized, and combined decision-making model	χ^2 (2, N = 90) = 5.60, $p > 0.05$

communication channels. The centralized model is considered when projects of similar type are clustered together, and monitoring of progress is performed under the same unit. The decentralized model enables decisions required at the site operational level. The operational level decisions can be decentralized, and tactical level decisions can be centralized. Table 9 shows the preference order of decision-making models. However, statistically, differences do not exist. Therefore, the mixed decision making is needed to execute the projects enabling proper communication, coordination, and collaborative channels. Exact approaches give the best solution but take much computational time and also complex; heuristics provide approximate solutions but may not be accurate; and metaheuristic can give optimal/near optimal solutions. The preference of solution methods is shown in Table 9. There exists a significant difference among the means (Table 10). It indicates that currently rule-based heuristics are widely used. However, respondents were suggested that robust approach is required to assist the real-time decision-making capabilities.

Resource sharing, dedicating, and substituting are useful for efficient use of limited available resources. It helps smooth functioning of multiple projects. However, it requires unmatched coordination among the multiple projects. The systematic solutions for these concepts are under-developed. Substituting resources are useful when finding same specification resources without affecting the project quality. Reactive and proactive planning is essential for these concepts. Many project management tools were used for its processes. However, the real-time monitoring and decision-making capability are always questionable, because of various multiproject environment aspects.

In the resource-constrained situation, the critical chain can be used. While preparing the baseline schedule of the project, periodic brainstorming should be done considering the construction techniques, risks, equipment, and manpower involved. Resource-constrained multiproject scheduling is more realistic and helps in achieving project targets with minimum deviation from milestones than resource-unconstrained schedules. The supply chain should interact for resource mobilization and identification of the source and place the orders well in advance as per microplanning. The synergy among stakeholders required to implement the project at corporate level planning, contract, site execution, monitoring, and control. Influence of BIM and other IT tools can combine to interact all stakeholders effectively, but BIM requires blend-in time to fit the organization. Due to the complexity of multiproject environment, experienced manpower should be deployed. The staff and labor should also be trained appropriately. Multiproject scheduling under resource-constrained situation requires more significant experience and can be done with the help of technologies.

5. Conclusions

There is a pressing need to find solution strategies for the resource-constrained multiproject scheduling problems since many companies work in the multiproject context with limited resources. The identified top challenging issues are (a) real-time monitoring and proactive decision making, (b) division and assignment of resources/resource allocation, (c) project management processes (information sharing), (d) coordination, (e) communication, and (f) competencies of project manager. Factor analysis identifies the following factors to improve the multiproject environment capabilities: (a) decision-related, (b) project environment-related, (c) project management-related, and (d) organization-related.

Resource-unconstrained situation does not address the issue of underutilization and wastage of resources leading to lower profit realization. The findings suggest that the following should be considered in resource management: identifying the work front, adopting pull planning approach, creating a common resource pool with resources allotted on a rental basis, a training programme to the staff, and finally migrating the mindset to the resource-constrained environment.

The resource-constrained situation needs to accommodate the following: prioritization of resources, coordination, communication, collaboration, unskilled labor, outdated machinery, unqualified supervision, quality issues, rework, and use of new technologies. The findings suggested top-up via subcontracting, proactive pull planning, introducing buffers (critical chain), proper training, working overtime, training the culture of the organization towards better communication, coordination, and collaboration and automating repetitive activities to improve the reliability of achieving baseline project performances.

Various multiproject strategies are suggested for effective management: explicit use of the multiproject approach in scheduling, the combined use of single and multimode activity execution modes, integrated nature of centralized and decentralized decision-making models, and robust solution approaches required to assist the real-time decision-making capabilities. Sharing, dedicating, and substituting resources which are highly relevant to the multiproject environment requires unmatched coordination. It was suggested that intelligent decision-making tools could enable efficient use of limited resources in the multiproject environment. The problems identified in the present study and the current practices that have been revealed through the survey are expected to contribute better project management in the construction industry. The limitation of this study is the smaller sample size. The future research directions could be (a) developing efficient decision-making algorithm for resource-constrained multiproject scheduling and (b) adopting a lean-based approach for the effective management of constrained resources.

Data Availability

The questionnaire survey data were collected confidentially and so cannot be made available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

A Unified Assessment Approach for Urban Infrastructure Sustainability and Resilience

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The concepts of sustainability and resilience have become very popular in the field of urban infrastructure. This paper reviews previous research on sustainability and resilience of urban infrastructure. The concepts of urban infrastructure's sustainability and resilience are compared from the perspectives of dimensions, properties, goals, and methodologies. The paper systematically assesses the sustainability and resilience of urban infrastructure by using the concept of the grade point average (GPA). The GPA of urban infrastructure's sustainability and resilience (urban infrastructure SR-GPA) is proposed as a unified concept. The assessment index system of urban infrastructure SR-GPA is constructed from five dimensions including demand, status, influence, resource, and measure. The analytic network process (ANP) is used to assess urban infrastructure SR-GPA considering the interaction between the indexes. The ANP structure model of urban infrastructure SR-GPA is established based on the assessment method and index system. The Harbin subway SR-GPA is selected as an empirical study to test the applicability of the proposed assessment method. The results show that the assessment indexes have different impacts on urban infrastructure SR-GPA. The Harbin subway SR-GPA is in a low level and can be upgraded through increasing construction investment, allocating resources efficiently, and considering resilience in the whole life cycle.

1. Introduction

The world is in the process of urbanization since the 20th century, and by far, the majority population live in cities [1, 2]. People construct numerous urban infrastructures to meet the various needs and challenges for urbanization [3–5]. These urban infrastructures exert significant influence on the global economy and environment and have become central to ensuring a sustainable future [6, 7]. Meanwhile, people need to confront tremendous technical, economic, and management risks to construct and operate urban infrastructures; therefore, we must build resilient infrastructure to overcome these risks [8]. Therefore, sustainability and resilience of urban infrastructure are vital to urbanization and social development. However, there have been very few researches on how to combine resilience and sustainability in a unified assessment methodology for the design, construction, and operation management of urban infrastructure.

Sustainability has become increasingly important in the civil engineering field with the global development of sustainability since the 1990s [9, 10]. Although most previous studies support life-cycle thinking in building sector with the model of the three sustainability dimensions and the importance of holistic analysis, fewer studies focus on urban infrastructure compared to building construction [11, 12]. Meanwhile, the concept of resilience is still considered novel and under development in the civil engineering field, and most studies focused on the conceptual and analytical definitions of resilience [12, 13].

Although the comprehensive description of resilience has been proposed from 11 different aspects in the civil engineering field, the studies of urban infrastructure's resilience are still under preliminary period [12, 14].

The researches of urban infrastructure sustainability and resilience are inefficient in previous studies. Moreover, there are few efforts to combine urban infrastructure sustainability and resilience into a unified concept.

The main cause of the above issue probably dues to the different historical origins of urban infrastructure sustainability and resilience. The theoretical and practical developments of resilience and sustainability are separate and without a mutual consideration of the findings in most domains [12]. Sustainability focuses on the influence of current behavior upon future development, and resilience emphasizes the response capability to abnormal impact [15, 16]. The concepts of sustainability and resilience have different historical roots, develop independently in both theoretical and practical field, but generate more and more common connotations as human society develops. Urban infrastructure should have properties of sustainability and resilience simultaneously during the construction and operation process to enhance its capabilities [9]. This study presents an effort to develop a unified concept for both urban infrastructure sustainability and infrastructure. The original contribution of this study consists of a unified assessment approach in order to address the sustainability and resilience of urban infrastructure simultaneously and quantitatively.

The paper is structured as follows: First, previous research on urban infrastructure sustainability and resilience are reviewed and summarized to explain the research motivation. Then, the concept of urban infrastructure SR-GPA is proposed for integrating the concepts of urban infrastructure sustainability and resilience. Afterward, the assessment index system and ANP structure model are constructed to design a unified assessment approach for urban infrastructure SR-GPA. Finally, Harbin subway is selected as an empirical study to test the applicability of the unified assessment approach.

2. Literature Review

2.1. Sustainability of Urban Infrastructure. Sustainability reflects the ability to sustain, which means the goal of sustainability is maintaining a state at a certain level [17–20]. The connotation of sustainability varies in different domains [21]. In the field of civil engineering, sustainability mainly refers to sustainable building, which devotes to improving the environmental performance of buildings through technical innovations [22]. Assessment standards enhance the sustainability of buildings, which can be reflected in the improved environmental performance [23]. Further researches have extended sustainability to other dimensions related to human development and emphasize the balance of environment, economy, and society [20, 24].

Current studies of urban infrastructure's sustainability mainly focus on the construction of the assessment index system and the selection of assessment methodology. From the view of whole life cycle, the urban infrastructure system generates interactions and feedback mechanisms with economic and social systems; thus, the assessment standards should be constructed from environmental, economic, social, and engineering dimensions [25]. From the perspective of improving urban infrastructure's environmental performance, the assessment indexes of sustainability can be divided into mandatory screening indexes and judgment indexes, which can be used to improve resource utilization efficiency [26, 27]. In theoretical and practical level, the assessment indexes of urban infrastructure's sustainability should include all dimensions of sustainability, and appropriate index parameters should be selected [28]. Some scholars have specifically studied different urban infrastructures' sustainability, such as lifelines, distributed infrastructure systems, and transportation systems [29–32].

Sustainability of urban infrastructure can be concluded as the unity of environmental, economic, and social dimension. The interactions of these three dimensions form a sustainable urban infrastructure that meets the needs of present and future generations for specific functions and services, and ensures the balanced development of economy, society, and environment.

2.2. Resilience of Urban Infrastructure. Resilience is the ability that a system restores to its original status after being disturbed [33]. The concept has been widely used in different domains (e.g., ecology and environment) [34]. In the field of civil engineering, engineers improve infrastructure's resilience to resist adverse impacts of extreme disasters, such as earthquake and hurricane [35]. Bruneau et al. conceptualize resilience from four interrelated dimensions: technical, organizational, social, and economic [14]. These four dimensions of resilience are described as the TOSE model. The TOSE model quantifies resilience from four properties: robustness, rapidity, redundancy, and resourcefulness [16]. Above four dimensions and four properties form conceptual framework for analyzing resilience. Under this conceptual framework, a resilient system is more reliable and can recover quickly, which ensure low socioeconomic consequences during a disaster [36]. Bocchini et al. systematically summarize the above eleven aspects of resilience for general civil infrastructure [12].

Urban infrastructure's resilience represents the ability that urban infrastructure can recover to its initial status through combinations of technical, economic, and management measures when facing unexpected situations or extreme disasters. Scholars have done research on the calculation and assessment methods of urban infrastructure's resilience from different perspectives which reflect the above eleven aspects of resilience. Various methods, such as simulation [37], mathematical calculation, and quantification method [38], have been used to calculate urban infrastructure's resilience. In addition, the priority of assessment standards should be considered for assessing urban infrastructure resilience, and policymakers' preferences play an important role in determining the assessment standards of resilience [39, 40].

Concluded from above studies, the assessment of urban infrastructure resilience should include three dimensions [12]: (1) technical dimension, comprising all technical elements in urban infrastructure life cycle; (2) economic dimension, involving economic factors in the restore processes of urban infrastructure; and (3) management dimension, incorporating social and organizational measures in operation and management stages of urban infrastructure. Moreover, the benefits of improving urban infrastructure resilience can be concluded as follows: (1) high reliability: urban infrastructure have lower probability of functional loss in the action of external disasters; (2) fast recovery: urban infrastructure can quickly restore to its normal status after disasters happen; and (3) low socioeconomic consequences: reducing negative impacts on society and economy by speeding up the recovery process of urban infrastructure.

2.3. Summary of Previous Research. Sustainability and resilience have different origins and evolve separately in theory and practice, although they share certain common connotations with the development of human society. There are some similarities between sustainability and resilience in the whole life cycle of urban infrastructure. Bocchini et al. compare similarities and differences between sustainability and resilience in the civil infrastructure domain [12]. The comparison is organized into eleven categories, and the possibility of conflation is evaluated. Due to the different origins, the common definitions of sustainability and resilience are not significantly matching [41]. Sustainability assessment mostly gives a score by using different quantitative and qualitative indicators, while resilience is usually calculated by quantified equation [42, 43]. These differences of sustainability and resilience cannot completely separate two concepts. Compared with these differences, the similarities between sustainability and resilience are more obvious.

As an important category to use for comparison, the dimensions of sustainability and resilience are perfectly matching. Social and economic dimensions are used for assessing both sustainability and resilience [44]. In addition, the technical and organizational dimensions of resilience are also important for sustainability [45]. At the theoretical level, some important instruments, such as LCC, multicriteria decision-making, can be used to assess sustainability and resilience. At the practical level, the assessment results of sustainability and resilience should be compared with previous reference experience [12]. From the point of view of decision-making, the targets of resilience focus on robustness and rapidity of systems, which can also reduce social and economic impacts [46]. Thus, the targets of sustainability and resilience are also good matching.

As the sustainability and resilience of urban infrastructure share so many similarities, scholars have attempted to combine these two concepts for assessment [47]. Zinke et al. summarize these preliminary attempts to combine sustainability and resilience in infrastructure projects [48]. Some conceptual descriptions are used to apply the properties of resilience on assessing urban infrastructure sustainability [12, 49, 50]. For instance, Turner describes some interesting approaches for combining two concepts in general and with a focus on vulnerability analyses [49]. Despite the fact that some existing schemes, such as British CEEQUAL [51] and American Envision (ISI 2011) [52], are primarily meant for assessing infrastructure sustainability, the assessment approaches described in these schemes also cover aspects associated with some resilience properties. Some sustainability assessment approaches cover risk-associated climate change, even though no further hazard-related consequences are addressed [53, 54].

The properties of sustainability are also incorporated in infrastructure resilience analysis. For instance, Ghosh et al. present an approach that combines embodied energy in the assessment of aging infrastructure exposed to seismic hazards [55]. Life-cycle energy assessment (LCEA) is used to extend the life-cycle cost analysis procedure for damages caused by hazards. The concept of sustainability is used to assess infrastructure resilience from environmental dimension. Rose incorporates a few sustainability properties in the concept of posthazard rehabilitation measures [47]. The results manifest improvements in conditions underlying sustainability that have helped in inherent and adaptive resilience associated with disaster recovery. The above analysis shows that urban infrastructure's sustainability and resilience can be considered and assessed together [56].

Urban infrastructure sustainability assessment only analyzes the predictable and regular influences of infrastructure from three dimensions: environment, economy, and society [57]. When infrastructure faces extreme events, infrastructure sustainability assessment is ineffective to enhance infrastructure performance [25]. On the other hand, resilience aims to analyze the responses of infrastructure due to extreme events and the ability of recovery under these circumstances [58]. If urban infrastructure resilience is considered separately on regular circumstances, the status of infrastructure will always be at a high level [59]. The resources will be wasted during the above process, which will have negative impacts on urban infrastructure sustainability [60]. Hence, urban infrastructure should be resilient and sustainable together, but it is very difficult to compare the performance of urban infrastructure by individual resilience assessments or sustainability assessments. A unified assessment approach should be constructed for assessing the sustainability and resilience of urban infrastructure together [12, 61].

3. Unified Assessment Approach

3.1. Urban Infrastructure SR-GPA. As mentioned in Section 2.3, sustainability and resilience have common connotations in whole life cycle of urban infrastructure. From the perspective of sustainability, urban infrastructure needs to meet human needs in normal status and quickly recover in unexpected situations; from the perspective of resilience, urban infrastructure improves the resilient capacity by technical, economic, and management measures, achieving sustainable development. Based on the above ideas, the National Council on Public Works Improvement (NCPWI) assessed the GPA (grade point average) of infrastructure with basic quality and expanding quality [62]. We constructed the unified concept of urban infrastructure's sustainability and resilience using GPA, which was named as the urban infrastructure SR-GPA (S is the abbreviation of sustainability

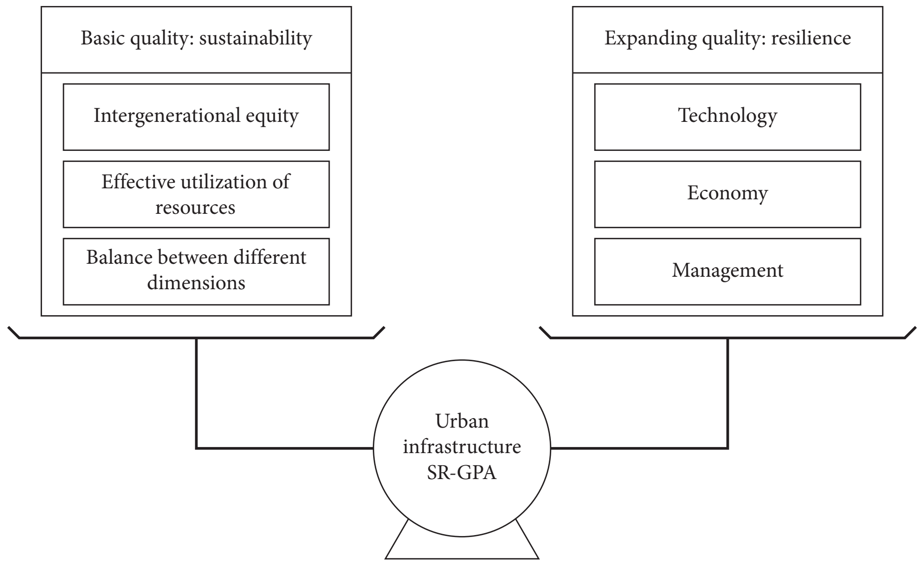

FIGURE 1: The concept of urban infrastructure SR-GPA.

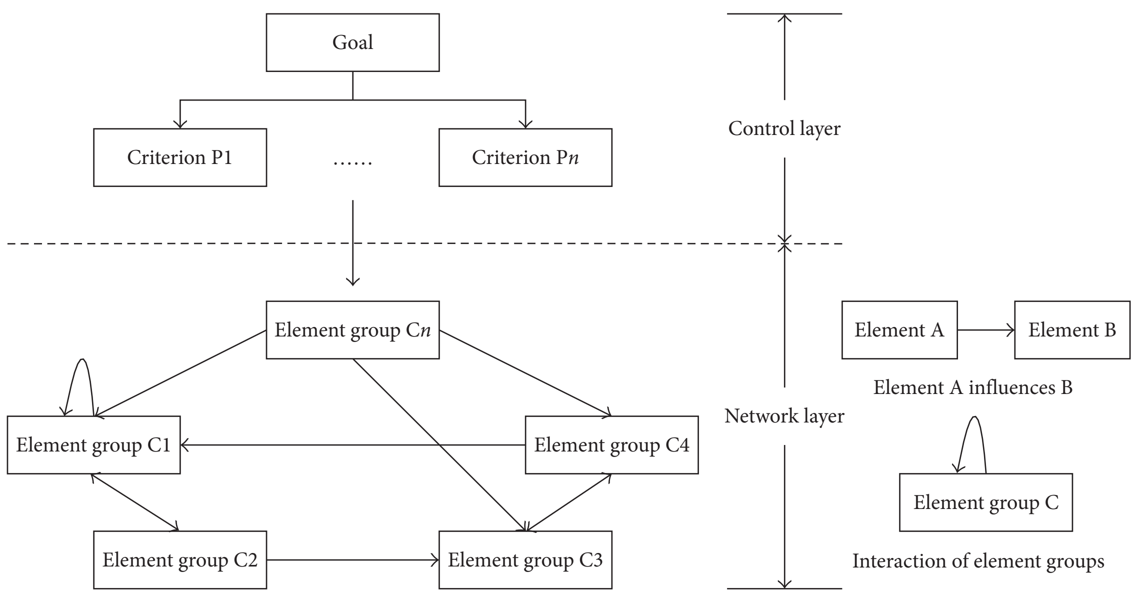

FIGURE 2: The typical hierarchical structure of ANP.

and R is the abbreviation of resilience). Urban infrastructure SR-GPA is described in Figure 1.

Figure 1 shows that urban infrastructure SR-GPA measures the basic quality and expanding quality of urban infrastructure. The basic quality and expanding quality of urban infrastructure, respectively, reflect its sustainability and resilience. Basic quality requires urban infrastructure to meet human needs in normal status and promote coordinated development which consists of intergenerational equity, effective resource utilization, and balanced economy, environment, and society. Expanding quality requires urban infrastructure to quickly restore to normal status by technical, economic, and management measures after the occurrence of unexpected situations such as earthquakes and hurricanes.

3.2. Assessment Method. The analytic network process (ANP) is a more general form of the analytic hierarchy process (AHP) which is used for multicriteria decision analysis. As ANP allows for complex interrelationships among decision levels and attributes, it has been widely used in infrastructure performance assessment [63, 64]. The composition of the analytic network process is described in Figure 2.

Figure 2 shows that the top element of the hierarchy is the overall goal of the decision model. The hierarchy decomposes from the general to a more specific attribute until a level of manageable decision criteria is met [65, 66]. ANP consists of clusters, elements, intercluster relations, and interelement relations. ANP reflects interaction and feedback between intracluster and intercluster. ANP contains

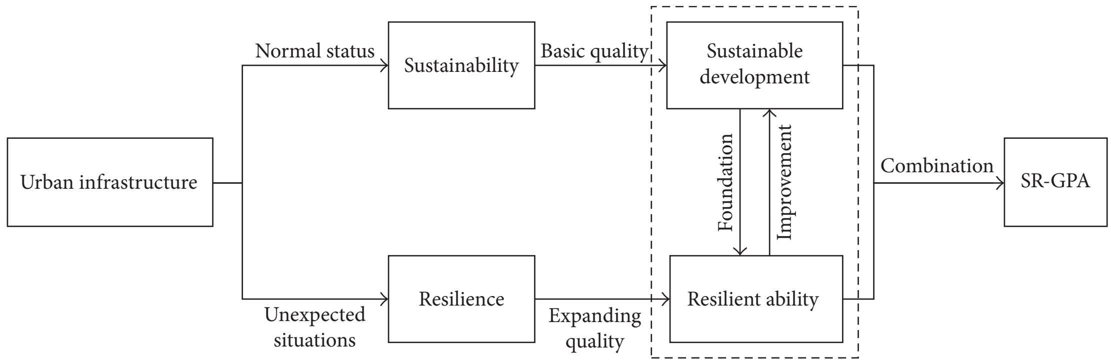

FIGURE 3: Combination framework of urban infrastructure sustainability and resilience.

two layers: the control layer, which includes goal and decision criteria, and the network layer, in which elements constitute mutually influent network structure [67]. Notably, all decisions are independent with each other and are only governed by target elements.

3.3. Assessment Index System

3.3.1. Combination Framework. Urban infrastructure sustainability assessment only analyzes the predictable and regular influences of urban infrastructure from different sustainable perspectives in normal status [57]. Traditional assessment methods of urban infrastructure sustainability is ineffective to improve urban infrastructure performance under extreme events [25]. Urban infrastructure resilience aims to analyze the responses of urban infrastructure due to extreme events and the ability of recovery under these circumstances [58]. The status of urban infrastructure is designed at a high level to satisfy the needs of urban infrastructure resilience, which has negative impacts on urban infrastructure sustainable development in normal status [59, 60]. It is unreasonable that urban infrastructure's sustainability and resilience are assessed separately. A unified assessment approach should be constructed for assessing the sustainability and resilience of urban infrastructure together [12, 61]. Urban infrastructure SR-GPA is proposed in Section 3.1 as the unified concept of urban infrastructure's sustainability and resilience. S is the abbreviation of urban infrastructure's sustainability, which requires that urban infrastructure should meet the development needs of human society from different sustainable perspectives in normal status [25]. R is the abbreviation of urban infrastructure's resilience, which requires that urban infrastructure should improve its resilient ability by technical, economic, and management measures in unexpected situations [68]. The combination framework of urban infrastructure's sustainability and resilience is shown in Figure 3.

Urban infrastructure performance is consisted of basic quality and expanding quality. Basic quality represents urban infrastructure sustainability which requires urban infrastructure to meet human needs in normal status and promote coordinated development from different sustainable perspectives [69]. Expanding quality represents urban infrastructure resilience which requires urban infrastructure to quickly recover to normal status by technical, economic, and management measures after the occurrence of unexpected situations [70]. From the perspective of sustainability, urban infrastructure meets human needs in normal status, which is the foundation of urban infrastructure resilience. From the perspective of resilience, urban infrastructure resilience is achieved by technical, economic, and management measures, which can improve urban infrastructure sustainability [12].

Previous studies of sustainable assessment focus on economic dimension, social dimension, and environmental dimension. Urban infrastructure sustainability has transformed from above traditional three dimensions to the following four dimensions: demand dimension [71], status dimension [72, 73], influence dimension [74, 75], and resource dimension [76–78]. Urban infrastructure resilience is mainly assessed from measure dimension, which reflects that urban infrastructure can quickly recover to normal status by technical, economic, and management measures after the occurrence of unexpected situations [8, 35, 79]. The assessment dimensions of urban infrastructure SR-GPA are shown in Figure 4.

3.3.2. Index Selection. This study develops the assessment index system of urban infrastructure SR-GPA which includes five dimensions: demand, status, influence, resource, and measure. The former four dimensions assess urban infrastructure's sustainability (basic quality), while the measure dimension represents urban infrastructure's resilience (expanding quality). The following sections explain the selection process of the assessment index from the above five dimensions:

(1) Demand Dimension. Urban economic development relies on the support of urban infrastructure. For example, higher urban economic development level requires more comprehensive infrastructures to ensure sustained growth [71]. This study selects the demand dimension index of urban infrastructure from three aspects: city size [80], economic development [25], and social level [81], which are shown in Table 1.

(2) Status Dimension. The state dimension indexes are mainly selected from the two aspects: the supply capacity

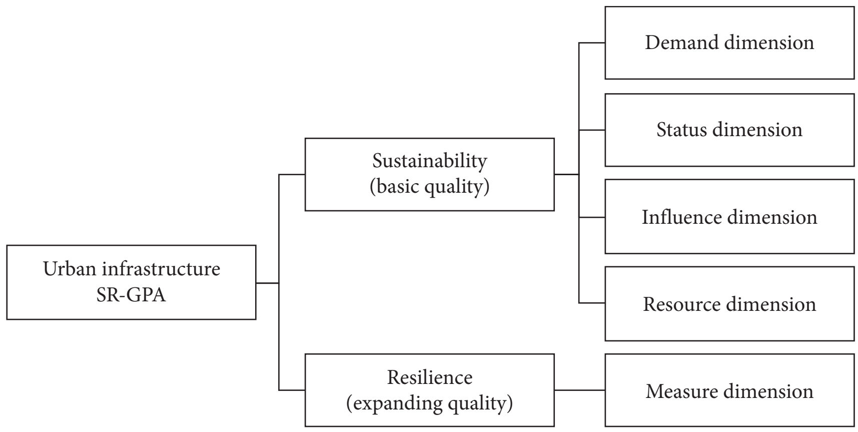

Figure 4: Assessment dimensions of urban infrastructure SR-GPA.

Table 1: Assessment index of demand dimension.

Dimension	Category	Index
Demand (D)	D1 city size	D1.1 growth rate of city resident population
	D2 economic development	D2.1 per capita GDP D2.2 proportion of tertiary industry in GDP D2.3 per capita disposable income
	D3 social level	D3.1 per financial income D3.2 per capital expenditure D3.3 growth rate of infrastructure investment

Table 2: Assessment index of status dimension.

Dimension	Category	Index
Status (S)	S1 supply capacity	S1.1 handling capacity S1.2 infrastructure density S1.3 proportion of built-up area in total area
	S2 public satisfaction	S2.1 service quality S2.2 service price S2.3 failure frequency S2.4 facility maintenance timeliness S2.5 facility maintenance quality

and public satisfaction. Supply capacity selects three indexes according to the authoritative statistical data published by statistics bureau, which are handling capacity, infrastructure density, and proportion of built-up area in total area [72, 73]. The three indexes are calculated as follows:

$$\text{Handling capacity}\,(\%) = \frac{\text{the population that urban infrastructure can serve}}{\text{total urban population}}, \tag{1}$$

$$\text{Infrastructure density}\,(\%) = \frac{\text{the urban area covered by infrastructure}}{\text{total urban area}}, \tag{2}$$

$$\text{Proportion of built} - \text{up area in total area}\ (\%) = \frac{\text{the infrastructure area}}{\text{total urban area}}. \tag{3}$$

Public satisfaction reflects the subjective feelings of the public to the service quality, service price, security, and reliability of urban infrastructure [82]. The assessment indexes of status dimension are shown in Table 2.

Table 3: Assessment index of influence dimension.

Dimension	Category	Index
Influence (I)	I1 goal	I1.1 improve community life quality I1.2 stimulate sustainable development I1.3 develop local technology
	I2 health	I2.1 improve public health and safety I2.2 reduce noise and vibration I2.3 reduce light pollution
	I3 social environment	I3.1 protect historical and cultural resources I3.2 protect local characteristics I3.3 protect the environment

Table 4: Assessment index of resource dimension.

Dimension	Category	Index
Resource (R)	R1 material	R1.1 reduce material usage R1.2 support sustainable procurement practices R1.3 use renewable materials R1.4 use local materials R1.5 dispose and recycle waste
	R2 energy	R2.1 reduce energy consumption R2.2 use renewable energy R2.3 monitor the energy system
	R3 water	R3.1 reduce water consumption R3.2 reduce domestic water R3.3 monitor the water system

(3) Influence Dimension. The fundamental purpose of the construction and operation of urban infrastructure is to improve the quality of people's life and promote sustainable development of urban economy and society [74]. The fundamental purpose of the construction and operation of urban infrastructure is to improve the quality of people's life and promote sustainable development of urban economy and society [74]. The influence dimension is further divided into three subcategories: goal, health, and social environment [25, 75]. The potential impacts should be assessed during the life cycle of urban infrastructure. The assessment indexes of influence dimension are shown in Table 3.

(4) Resource Dimension. Using the efficiency of resources has direct impacts on the sustainability of urban infrastructure because its construction and operation consume large amounts of resources. The assessment indexes of resource dimension, which were developed based on previous research on resource efficiency of urban infrastructure, include three main categories, that is, material, energy, and water. In the construction phase, sustainable infrastructure should efficiently use all materials to reduce the "embodied energy," which is consumed in the process of material production and transportation [76]. In the operation phase, sustainable infrastructure should minimize the overall energy consumption and consider the efficient use of multiple energy sources [77]. Moreover, urban infrastructure should reduce the overall water consumption and consider the positive or negative impacts on water resources [78]. The detailed breakdown of the assessment indexes of resource dimension is shown in Table 4.

(5) Measure Dimension. The assessment indexes of measure dimension mainly reflect the resilience of urban infrastructure, and were selected from three aspects including technical innovation, economic support, and management measures. Technical innovation includes innovations not only in raw materials, products, processes, and equipment but also in the management process and organizational change [79]. The economic support involves in the construction and maintenance of urban infrastructure [8]. On the one hand, the development and use of new materials and technologies, which improve the resilience of urban infrastructure, require a lot of capital. On the other hand, the maintenance, repair, and improvement of urban infrastructure require abundant economic supports. Management measures enhance the resilience of urban infrastructure and ensure urban infrastructure to have a longer service life that meets the future needs [35]. Through the above analysis, the assessment indexes of measure dimension are shown in Table 5.

3.3.3. Index Quantification. The developed assessment indexes include both qualitative and quantitative indexes. Qualitative indexes are difficult to describe with quantitative data, and quantitative indexes can be quantified directly with quantitative data. According to the interaction between index meaning and value, quantitative indexes are divided into benefit indexes and cost indexes. The score of benefit indexes has positive impacts on urban infrastructure GPA, and the score of cost indexes has negative impacts on urban infrastructure GPA. The classification situations of assessment indexes are

Table 5: Assessment index of measure dimension.

Dimension	Category	Index
Measure (M)	M1 technology innovation	M1.1 new materials, technology, and equipment
		M1.2 intelligent monitoring system
		M1.3 collaborative innovation
	M2 economic support	M2.1 innovation investment
		M2.2 investment on maintenance
		M2.3 effective management capital
	M3 management measure	M3.1 evaluate climate change risks
		M3.2 enhance long-term adaptation
		M3.3 improve withstanding ability to extreme events

Table 6: Assessment index system of urban infrastructure SR-GPA.

Dimension	Category	Index	Property
Demand (D)	D1 city size	D1.1 growth rate of city resident population	C
	D2 economic development	D2.1 per capita GDP	B
		D2.2 proportion of tertiary industry in GDP	B
		D2.3 per capita disposable income	B
	D3 social level	D3.1 per financial income	B
		D3.2 per capital expenditure	B
		D3.3 growth rate of infrastructure investment	B
Status (S)	S1 supply capacity	S1.1 handling capacity	B
		S1.2 infrastructure density	B
		S1.3 proportion of built-up area in total area	B
	S2 public satisfaction	S2.1 service quality	Q
		S2.2 service price	Q
		S2.3 failure frequency	Q
		S2.4 facility maintenance timeliness	Q
		S2.5 facility maintenance quality	Q
Influence (I)	I1 goal	I1.1 improve community life quality	Q
		I1.2 stimulate sustainable development	Q
		I1.3 develop local technology	Q
	I2 health	I2.1 improve public health and safety	Q
		I2.2 reduce noise and vibration	Q
		I2.3 reduce light pollution	Q
	I3 social environment	I3.1 protect historical and cultural resources	Q
		I3.2 protect local characteristics	Q
		I3.3 protect the environment	Q
Resource (R)	R1 save material	R1.1 reduce material usage	Q
		R1.2 support sustainable procurement practices	Q
		R1.3 use renewable materials	Q
		R1.4 use local materials	Q
		R1.5 dispose and recycle waste	Q
	R2 save energy	R2.1 reduce energy consumption	Q
		R2.2 use renewable energy	Q
		R2.3 monitor the energy system	Q
	R3 save water	R3.1 reduce water consumption	Q
		R3.2 reduce domestic water	Q
		R3.3 monitor the water system	Q
Measure (M)	M1 technology innovation	M1.1 new materials, technology, and equipment	Q
		M1.2 intelligent monitoring system	Q
		M1.3 collaborative innovation	Q
	M2 economic support	M2.1 innovation investment	Q
		M2.2 investment on maintenance	Q
		M2.3 effective management capital	Q
	M3 management measure	M3.1 evaluate climate change risks	Q
		M3.2 enhance long-term adaptation	Q
		M3.3 improve withstanding ability to extreme events	Q

Note. C, cost index; B, benefit index; Q, qualitative index.

summarized in Table 6. The assessment indexes of former four dimensions in Table 6 present urban infrastructure sustainability (basic quality), while the assessment indexes of measure dimension in Table 6 present urban infrastructure resilience (expanding quality).

In the assessment index system of urban infrastructure SR-GPA, qualitative indexes are quantified by the 5-point expert grading method, while quantitative indexes are quantified by the efficiency coefficient method. The quantification processes are as follows:

$$\text{Score of benefit index} = 1 + 4 \times \frac{\text{actual value} - \text{forbidden value}}{\text{satisfied value} - \text{forbidden value}}, \tag{4}$$

$$\text{Score of cost index} = 1 + 4 \times \frac{\text{forbidden value} - \text{actual value}}{\text{forbidden value} - \text{satisfied value}}. \tag{5}$$

Equations (4) and (5), respectively, select the highest value and the lowest value of each quantitative index as the satisfied value and forbidden value. According to the 5-point expert grading method, the basic value and the highest value of each quantitative index are 1 and 5, respectively.

3.4. ANP Structure Model of Urban Infrastructure SR-GPA. The assessment indexes set of ANP is as follows:

$$\mathrm{U} = \{\mathrm{U}_1, \mathrm{U}_2, \ldots, \mathrm{U}_k, \ldots, \mathrm{U}_n\}, \quad k = 1, 2, \ldots, n, \tag{6}$$

which includes first-level indexes, where n represents the number of first-level indexes in set U. Each first-level index includes several second-level indexes as follows:

$$\mathrm{U}_k = \left\{\mathrm{U}_{k1}, \mathrm{U}_{k2}, \ldots, \mathrm{U}_{ki}, \ldots, \mathrm{U}_{kn_k}\right\}, \quad i = 1, 2, \ldots, n_k, \tag{7}$$

which is a second-level indexes set, where n_k represents the number of second-level indexes in set U_k. Each second-level index includes several third-level indexes as follows:

$$\mathrm{U}_{ki} = \left\{\mathrm{U}_{ki1}, \mathrm{U}_{ki2}, \ldots, \mathrm{U}_{kij}, \ldots, \mathrm{U}_{kin}\right\}, \quad j = 1, 2, \ldots, n_{ki}, \tag{8}$$

which is the third-level indexes set, where n_{ki} represents the number of third-level indexes in set U_{ki}.

According to the above method, the assessment index system of urban infrastructure SR-GPA is divided into first-level indexes, second-level indexes, and third-level indexes. The ANP structure model of urban infrastructure SR-GPA is constructed through interaction between indexes as shown in Figure 5.

Figure 5 shows that the ANP structure model of urban infrastructure SR-GPA contains the control layer and network layer. The control layer includes goal and decision criteria. Urban infrastructure SR-GPA is the goal of the control layer, and the five dimensions and indexes are the decision criteria of the control layer. The network layer is the influence relationship between five dimensions and indexes. The ANP structure model of urban infrastructure SR-GPA considers the interaction between indexes and allocates weight to each index. Based on the quantification of indexes, the weighted synthesis model is used to calculate the comprehensive score, which describes urban infrastructure's sustainability and resilience. The basic equation of the weighted synthesis model is as follows:

$$y = \sum_{i=1}^{m} w_i x_i, \tag{9}$$

where w_i is the weight of the index, x_i is the quantitative score, and y is the final score.

4. Case Study

4.1. Case Background. Harbin subway is an urban transport system located in Harbin, Heilongjiang Province. It is the first subway system in the alpine region of China. The general plan of the Harbin subway has a total operation mileage of 340 km, which includes twelve main lines, one circle line, and two branch lines. The total investment will reach 30 billion dollars, and the construction of the entire project will last for 20 years. Currently, line 1 of the Harbin subway, which includes 25 stations with a length of 27.3 km, has been operated since September 26, 2013 [83].

This paper takes the Harbin subway as the research object (case study) because it is a typical urban infrastructure which possesses the following characteristics: high investment, long construction period, and remarkable social and economic impacts. The sustainability and resilience of the Harbin subway determine whether such mega urban infrastructure will meet the current and future needs of the city. An empirical research on the sustainability and resilience of the Harbin subway was performed by using the proposed urban infrastructure SR-GPA assessment method. We analyzed whether current sustainability and resilience status of the Harbin subway project can meet the needs of city development. Finally, problems of Harbin subway's sustainability and resilience were found, which could guide its future construction and operation.

4.2. Data Collection. The assessment indexes in Table 6 can be divided into three parts according to index properties. The assessment indexes of influence, resource, and measure dimensions reflect the sustainability and resilience of the Harbin subway from technical perspective. It is suitable that the quantitative score of these technical assessment indexes are obtained from related professional staff, such as designers,

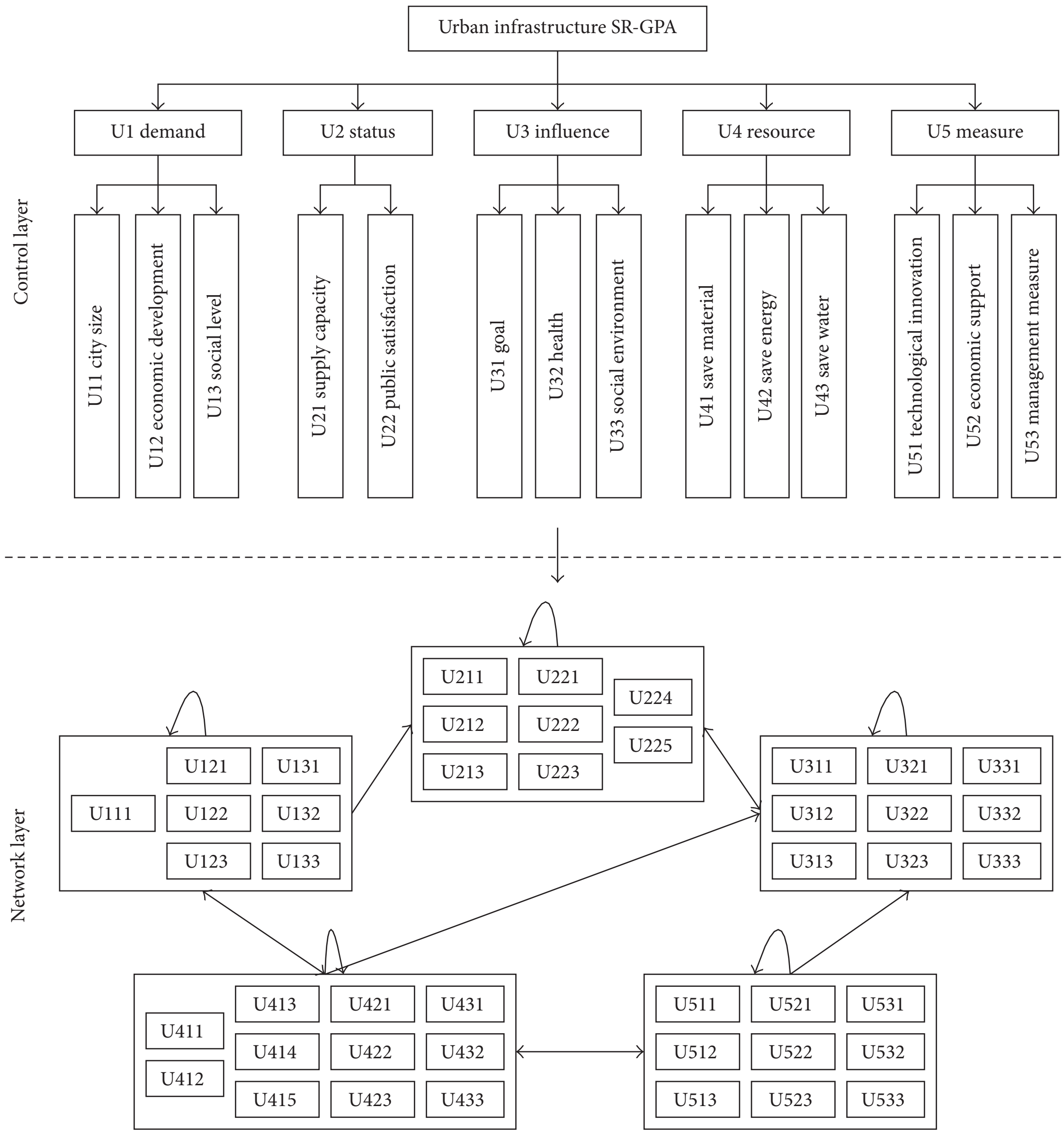

Figure 5: ANP structure model of urban infrastructure SR-GPA.

constructors, and operators [25, 84]. The quantitative assessment indexes of public satisfaction in status dimension reflect the service level of the Harbin subway from the perspective of social sustainability. Thus, the quantitative score of assessment indexes in public satisfaction mainly depends on the subjective assessment of urban infrastructure users. The assessment indexes of demand dimension and supply capacity in status dimension objectively reflect the sustainability of the Harbin subway. These objective assessment indexes are closely related to the level of urban infrastructure demands [85]. Thus, the quantitative score of these objective assessment indexes are mainly obtained by comparing related indexes of cities with similar urban infrastructure demands in previous studies [25, 86]. Through the above analysis on data collection, the data sources of the case study are summarized in Figure 6.

According to the assessment indexes of influence, resource, and measure dimensions, we select designers, constructors, and operators of the Harbin subway as respondents and collect data of qualitative indexes through questionnaires. A total of 100 questionnaires were sent out by Email with 53 valid questionnaires retrieved. Table 7 is the category distribution of respondents according to the type of work, work experience, and the number of involving projects.

According to the quantitative assessment indexes of public satisfaction in status dimension, we take passengers of the Harbin subway as respondents. A total of 400 questionnaires were sent out at stations of Harbin subway line 1 with 236 valid questionnaires retrieved. Figure 7 shows the age distribution of respondents.

According to other quantitative assessment indexes, we select fifteen major cities as samples, that is, Harbin, Hangzhou, Suzhou, Xi’an, Zhengzhou, Qingdao, Changchun, Kunming, Dalian, Changsha, Taiyuan, Jinan, Hefei, Foshan, and Urumqi. The urban resident population of the

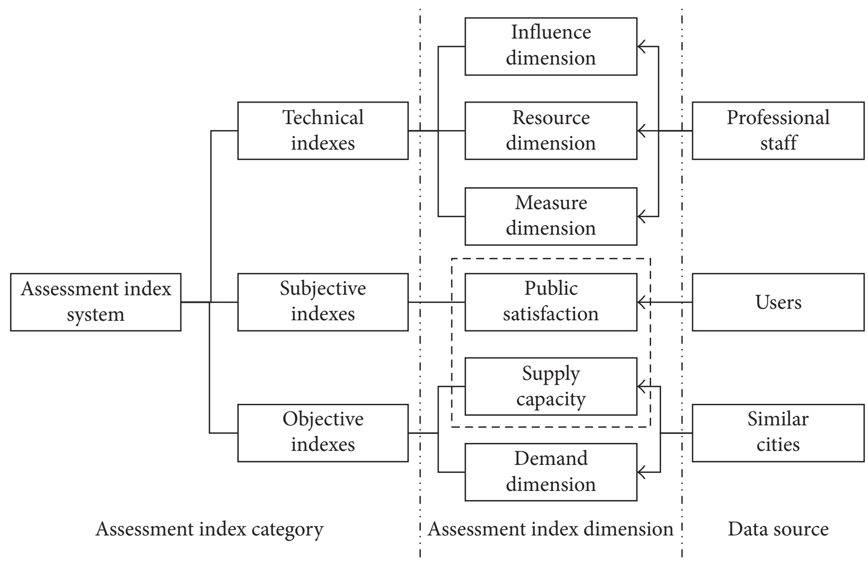

FIGURE 6: Data sources of the case study.

TABLE 7: Category distribution of respondents.

Basis of classification	Classification criterion	Frequency	Percentage (%)
Type of work	Design	11	20.8
	Construct	25	47.2
	Operation	17	32.1
Work experience	Below 5 years	7	13.2
	6–10 years	11	20.8
	11–15 years	14	26.4
	Above 16 years	21	39.6
Number of involving projects	Below 2	5	9.4
	3–5	11	20.8
	6–10	13	24.5
	Above 11	24	45.3

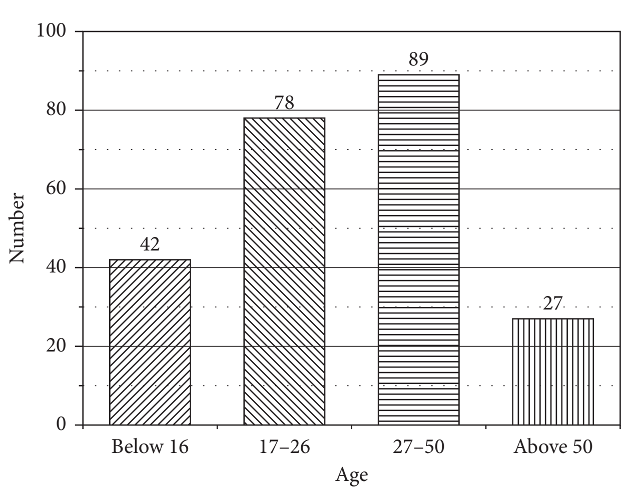

FIGURE 7: Age distribution of respondents.

above fifteen cities is between one million and five million, which means that these cities have similar urban infrastructure demands. The efficacy coefficient method is used to calculate the quantitative scores of quantitative indexes in demand and status dimensions.

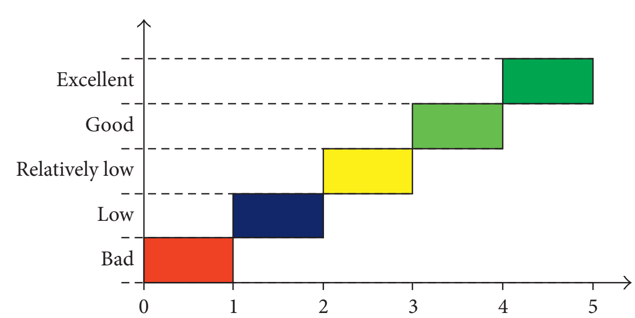

FIGURE 8: Judgment criterion of urban infrastructure SR-GPA.

4.3. Result Analysis

4.3.1. Index Score Analysis. In the Section 3.3.3, the assessment indexes of urban infrastructure SR-GPA are quantified by the 5-point expert grading method. Thus, the score of each index is between 0 and 5. Through comparing existing GPA standards [87], the judgment criterion of urban infrastructure SR-GPA is summarized in Figure 8.

The horizontal axis represents the score of urban infrastructure SR-GPA, and the vertical axis represents the level

Table 8: The quantitative score of assessment index.

Dimension	Category	Index	Score
Demand (D)	D1 city size	D1.1 growth rate of city resident population	5.00
	D2 economic development	D2.1 per capita GDP	1.00
		D2.2 proportion of tertiary industry in GDP	4.16
		D2.3 per capita disposable income	1.87
	D3 social level	D3.1 per financial income	1.13
		D3.2 per capital expenditure	1.39
		D3.3 growth rate of infrastructure investment	1.90
Status (S)	S1 supply capacity	S1.1 handling capacity	1.33
		S1.2 infrastructure density	1.02
		S1.3 proportion of built-up area in total area	1.47
	S2 public satisfaction	S2.1 service quality	4.26
		S2.2 service price	4.79
		S2.3 failure frequency	4.84
		S2.4 facility maintenance timeliness	4.66
		S2.5 facility maintenance quality	4.81
Influence (I)	I1 goal	I1.1 improve community life quality	3.40
		I1.2 stimulate sustainable development	3.41
		I1.3 develop local technology	2.61
	I2 health	I2.1 improve public health and safety	3.01
		I2.2 reduce noise and vibration	3.02
		I2.3 reduce light pollution	3.15
	I3 social environment	I3.1 protect historical and cultural resources	4.32
		I3.2 protect local characteristics	4.53
		I3.3 protect the environment	2.73
Resource (R)	R1 save material	R1.1 reduce material usage	1.03
		R1.2 support sustainable procurement practices	1.75
		R1.3 use renewable materials	1.85
		R1.4 use local materials	2.45
		R1.5 dispose and recycle waste	4.03
	R2 save energy	R2.1 reduce energy consumption	2.02
		R2.2 use renewable energy	1.63
		R2.3 monitor the energy system	1.25
	R3 save water	R3.1 reduce water consumption	3.22
		R3.2 reduce domestic water	2.89
		R3.3 monitor the water system	1.05
Measure (M)	M1 technology innovation	M1.1 new materials, technology, and equipment	4.26
		M1.2 intelligent monitoring system	3.58
		M1.3 collaborative innovation	0.26
	M2 economic support	M2.1 innovation investment	0.92
		M2.2 investment on maintenance	2.90
		M2.3 effective management capital	2.04
	M3 management measure	M3.1 evaluate climate change risks	1.02
		M3.2 enhance long-term adaptation	0.62
		M3.3 improve withstanding ability to extreme events	2.37

of urban infrastructure SR-GPA. The urban infrastructure SR-GPA is divided into five levels: excellent, good, relatively low, low, and bad. Different color bars represent different score levels of assessment indexes. The above five levels correspond to five score intervals of urban infrastructure SR-GPA which are 4 to 5, 3 to 4, 2 to 3, 1 to 2, and 0 to 1.

According to the quantitative methods of urban infrastructure SR-GPA, we quantitate the data of assessment indexes and calculate the quantitative scores of indexes in the Harbin subway SR-GPA assessment index system. The quantitative scores of assessment indexes are shown in Table 8.

Table 8 summarizes the score level of each index from five dimensions, and the analysis results are as follows:

(1) Demand Dimension. The score of index D1.1 is 5, which means that the level of D1 city size is excellent. The score of index D1.1 also reflects that the Harbin subway can satisfy the growth demand of city resident population. The level of the score of most indexes in D2 economic development and D3 social level is low. These reflect that Harbin has a disadvantage on sustainable development level compared with cities of similar scale. The low-speed urban expansion of Harbin results in less pressure on the investment of Harbin subway.

(2) Status Dimension. The supply capacity of the Harbin subway is low, which is reflected by the low score of handling

capacity, infrastructure density, and proportion of built-up area in total area, while the score of index of public satisfaction is good, which reflects the public is satisfied with the service of Harbin subway. The results meet the real situation that Harbin subway is just put into use and only operates line 1 currently.

(3) Influence Dimension. From the perspective of I1 goal, the Harbin subway plays a positive role in improving people's quality of life and promoting sustainable economic and social development. The Harbin subway takes measures to reduce the light pollution, noise and vibration, and other negative effects in the construction process, and the scores of indexes in I2 health are good. The construction of the Harbin subway has realized the organic combination with the social environment and historical development. Harbin's humanistic environment is consciously protected, which strengthen cultural heritage and public identity. It is particularly prominent that the Harbin subway can protect historical and cultural resources. The average score of indexes in I3 social environment is excellent. In general, the Harbin subway has positive influence on the sustainable development of Harbin.

(4) Resource Dimension. The scores of most indexes in R1 save material are low, which indicates that the Harbin subway lacks the assessment of total materials energy consumption in the process of construction and operation from the perspective of life cycle. The Harbin subway is more inclined to use local materials and focuses on waste disposal and recycling. The score of support sustainable procurement practices and use renewable materials are low. The Harbin subway has poor performance of saving energy, which is reflected by the low or relatively low score of reducing energy consumption, using renewable energy and energy monitor system. The construction of the Harbin subway has involved great efforts in water saving, which is reflected by the good score of R3.1 reduce water consumption.

(5) Measure Dimension. The Harbin subway focuses on the application of new materials, technologies, and equipment in the process of construction and operation. The intelligent detection system is used to monitor the operation situation of Harbin subway. Thus, the scores of indexes in M1.1 new materials, technology, and equipment and M1.2 intelligent monitoring system are excellent and good. The bad score of M1.3 collaborative innovation reflects that new technologies should be implicated by innovation investment and collaborative innovation among enterprises, universities, and research institutions. The scores of indexes in M2 economic support and M3 management measure are below good level, which means that the Harbin subway should take economic and management measures to enhance long-term resilience and emphasize on monitoring responding to extreme events in the operational phase.

4.3.2. Measuring Result Analysis. According to the ANP structure model of urban infrastructure SR-GPA, the calculation result of weight is summarized in Table 9.

Table 9 shows that the weights of different indexes have great differences. The weights of influence and measure dimension are relatively large, which indicates that these indexes are crucial in improving urban infrastructure SR-GPA. The weights of demand dimension are relatively small, which indicates that urban development level has small impacts on urban infrastructure SR-GPA. Combined with quantitative scores and ultimate limit weight, the final scores of indexes are summarized from five dimensions and fourteen categories (Table 10).

Table 10 shows final score levels of indexes from different dimensions and categories. According to the judgment criterion of urban infrastructure SR-GPA, the score of City size is excellent, which means that the Harbin subway can satisfy the growth demand of city resident population and the construction of the Harbin subway does not exert excessive pressure. Considering long-term development of Harbin, the scores of Economic development and Social level are low, and Harbin subway cannot meet the long-term demands of urban sustainable development. From the perspectives of status and influence dimensions, the scores of these two dimensions are good. The Harbin subway improves people's living standards and promotes economic and social development of the city. From the perspective of resource dimension, the Harbin subway lacks practical measures on saving material, energy, and water. Thus, the score of resource dimension is low. From the perspective of measure dimension, the Harbin subway does not consider technical, economic, and management measures systematically, and its resilience is not considered in the whole life cycle.

Overall, the Harbin subway SR-GPA is 2.6277, which is a relatively low level. The Harbin subway SR-GPA can be upgraded by improving assessment indexes which have relatively low, low, and bad level scores. According to Table 10, these assessment indexes are focus on demand dimension, supply capacity in status dimension, resource dimension and measure dimension. The Harbin subway SR-GPA should be enhanced using the following three aspects:

(1) The supply capacity of the Harbin subway should be improved by increasing the construction investment: cities have different demands for infrastructure, and the size of cities should be matched with the demands of infrastructure. Harbin's economic and social development indexes are in low levels. More infrastructures are required to ensure the expansion of urban scale, economic development, and social progress. To promote sustainable development, Harbin should increase the investment in subway construction and ensure the effective use of construction funds. A complete network of the Harbin subway enhances the supply capacity of the Harbin subway, which can meet the needs of sustainable development.

(2) In the process of construction and operation, the Harbin subway should efficiently allocate resources and implement sustainable development practices: the scores of assessment indexes in resource dimension are all below good level. The construction and operation of infrastructure cannot avoid the

Table 9: The ultimate limit weight of assessment index.

Dimension	Category	Index	Weight
Demand (D)	D1 city size	D1.1 growth rate of city resident population	0.00132
	D2 economic development	D2.1 per capita GDP	0.00402
		D2.2 proportion of tertiary industry in GDP	0.00142
		D2.3 per capita disposable income	0.00191
	D3 social level	D3.1 per financial income	0.00148
		D3.2 per capital expenditure	0.00404
		D3.3 growth rate of infrastructure investment	0.00587
Status (S)	S1 supply capacity	S1.1 handling capacity	0.00146
		S1.2 infrastructure density	0.00652
		S1.3 proportion of built-up area in total area	0.00774
	S2 public satisfaction	S2.1 service quality	0.01453
		S2.2 service price	0.00018
		S2.3 failure frequency	0.00209
		S2.4 facility maintenance timeliness	0.00963
		S2.5 facility maintenance quality	0.00994
Influence (I)	I1 goal	I1.1 improve community life quality	0.07062
		I1.2 stimulate sustainable development	0.06409
		I1.3 develop local technology	0.06313
	I2 health	I2.1 improve public health and safety	0.05791
		I2.2 reduce noise and vibration	0.02279
		I2.3 reduce light pollution	0.01972
	I3 social environment	I3.1 protect historical and cultural resources	0.02714
		I3.2 protect local characteristics	0.03264
		I3.3 protect the environment	0.03515
Resource (R)	R1 save material	R1.1 reduce material usage	0.03137
		R1.2 support sustainable procurement practices	0.03076
		R1.3 use renewable materials	0.02466
		R1.4 use local materials	0.02109
		R1.5 dispose and recycle waste	0.02024
	R2 save energy	R2.1 reduce energy consumption	0.03113
		R2.2 use renewable energy	0.02923
		R2.3 monitor the energy system	0.02246
	R3 save water	R3.1 reduce water consumption	0.03008
		R3.2 reduce domestic water	0.02876
		R3.3 monitor the water system	0.01818
Measure (M)	M1 technology innovation	M1.1 new materials, technology, and equipment	0.03933
		M1.2 intelligent monitoring system	0.01916
		M1.3 collaborative innovation	0.01579
	M2 economic support	M2.1 innovation investment	0.03168
		M2.2 investment on maintenance	0.03292
		M2.3 effective management capital	0.02027
	M3 management measure	M3.1 evaluate climate change risks	0.01844
		M3.2 enhance long-term adaptation	0.02675
		M3.3 improve withstanding ability to extreme events	0.02936

consumption of resources; the efficiency of resources utilization has direct impacts on the sustainability of infrastructure. The construction of the Harbin subway lacks clear advantages in resources utilization and shows disadvantages in using renewable materials and energy. To improve the sustainability of the Harbin subway, it is necessary to allocate resources rationally and comprehensively from the aspects of saving material, energy, and water.

(3) The consumption of materials, energy, and water should be assessed from the perspective of whole life cycle, and the construction of the Harbin subway should find ways to reduce resource consumption. The Harbin subway should choose suppliers who consider economic, social, and environmental impacts in the process of production and select suppliers with good reputation and ethical responsibility. In addition to these measures, the monitoring system should be used to monitor material consumption, energy use, and water consumption. All the above measures can improve the scores of assessment indexes in resource dimension.

(4) The resilience of the Harbin subway should be improved by economic support and management measure: the resilience of infrastructure reflects its adaptive ability to changing conditions in the long term as well

Table 10: The quantitative score of SR-GPA.

Goal	Dimension	Category	Score
Harbin subway SR-GPA (2.6277)	Demand (1.9212)	City size	5
		Economic development	1.8366
		Social level	1.6191
	Status (3.5618)	Supply capacity	1.2704
		Public satisfaction	4.5522
	Influence (3.1222)	Goal	3.1512
		Health	2.4212
		Social environment	3.8035
	Resource (2.0928)	Save material	2.0684
		Save energy	1.6735
		Save water	2.5846
	Measure (1.5612)	Technology innovation	3.2343
		Economic support	1.4683
		Management measure	0.4748

as its rapid recovery capabilities in emergency situations. The resilience of infrastructure should be considered in whole life cycle including the optimization of structural design and the use of new materials, technologies, and equipment. The risks should be comprehensively assessed to enhance infrastructure's long-term adaptive capacity and quick response capacity in case of unexpected conditions. The Harbin subway applied the advanced monitoring system in the operation process and shows good response ability to unexpected situations.

(5) The score of the Harbin subway economic support index is low, and the score of Harbin subway management measure index is even bad. Thus, the resilience of the Harbin subway should also be improved by strengthening management in design and construction phases. During the design phase, cooperation between enterprises, universities, research institutions, and other organizations should be strengthened to promote technological innovation and design optimization, therefore improving the resilience of the Harbin subway. The Harbin subway should sustain a series of changes in natural conditions, such as temperature changes, precipitation, and seasonal hydrological conditions. The decentralized system should be designed to make the Harbin subway maintain a certain function even if some components are damaged. During the construction phase, the Harbin subway should monitor climate changes, the emergence of extreme weather, and other natural disasters. Emergency plan should be developed in advance to improve the response and recovery speed of the Harbin subway to extreme events.

5. Discussion

Sustainability and resilience have different origins and evolve separately in theory and practice. Due to the different origins, the definitions of sustainability and resilience present significant differences [41]. The sustainability assessment of urban infrastructure mostly depends on different quantitative and qualitative indicators, while the resilience assessment of urban infrastructure usually focuses on quantified equation [42, 43]. Urban infrastructure sustainability and resilience are separated in most previous studies.

Urban infrastructure sustainability assessment only analyzes the regular performances of urban infrastructure from different sustainable perspectives in normal status [57]. These assessment methods of urban infrastructure sustainability are ineffective to improve urban infrastructure performance under extreme events [25]. Urban infrastructure resilience assessment mainly analyzes the responses of urban infrastructure due to extreme events and the ability of recovery under these circumstances [58]. The status of urban infrastructure is designed at a high level to satisfy the needs of urban infrastructure resilience, which has negative impacts on urban infrastructure sustainable development in normal status [59, 60]. Thus, the sustainability and resilience of urban infrastructure should be considered and assessed together [56].

Previous studies have attempted to combine these two concepts for assessment [47]. Some conceptual descriptions are used to combine some specific properties of resilience into urban infrastructure sustainability [12, 49, 50]. More and more urban infrastructure sustainability assessment approaches cover risk-associated climate change, even though no further hazard-related consequences are addressed [53, 54]. Previous studies also incorporated the properties of sustainability in infrastructure resilience analysis [55]. Urban infrastructure resilience is mainly assessed from the environment and economic perspectives of sustainability [47]. Thus, previous studies did not really combine urban infrastructure sustainability and resilience. Urban infrastructure resilience is considered as the branch of urban infrastructure sustainability under extreme events. Urban infrastructure sustainability is selected as the goals of urban infrastructure resilience. Urban infrastructure sustainability and resilience are essentially two separate concepts on previous studies.

This study proposed a new unified assessment approach for urban infrastructure sustainability and resilience using the concept of urban infrastructure SR-GPA. The GPA of urban infrastructure's sustainability and resilience (urban infrastructure SR-GPA) is proposed as a unified concept. The assessment index system of urban infrastructure SR-GPA is constructed from five dimensions including demand, status, influence, resource, and measure. The analytic network process (ANP) is used to assess urban infrastructure SR-GPA considering the interaction between the indexes. The ANP structure model of urban infrastructure SR-GPA is established based on the assessment method and index system. This new assessment approach bridged the above gaps that the sustainability and resilience of urban infrastructure were separated on existing researches. This study provided strong supports for academic and industrial fields to assess, analyze, enhance, and optimize the sustainability and resilience of urban infrastructure together.

6. Conclusions

This paper systematically reviewed previous studies of urban infrastructure's sustainability and resilience. To mutually assess the sustainability and resilience of urban infrastructure, the paper proposed the concept of urban infrastructure SR-GPA and constructed the urban infrastructure SR-GPA assessment index system and ANP structure model. Taking the Harbin subway as the research object, the Harbin subway SR-GPA was assessed and analyzed, with promotion strategies proposed to improve Harbin subway's sustainability and resilience.

The main achievements of this study are as follows: (1) *proposing the concept of urban infrastructure SR-GPA*: analyzed the research status of urban infrastructure sustainability and resilience, integrated the concepts of sustainability and resilience into urban infrastructure GPA assessment, and defined the concept of urban infrastructure SR-GPA; (2) *constructing the urban infrastructure SR-GPA assessment index system and ANP structure model*: from demand, status, influence, resources, and measures dimensions, the built urban infrastructure SR-GPA assessment index system calculated the quantitative scores of qualitative and quantitative indexes, respectively, through questionnaires and the efficiency coefficient method, and formed the ANP structure model to assess urban infrastructure SR-GPA; and (3) *assessing the Harbin subway SR-GPA*: calculated quantitative scores and ultimate limit weight of indexes in the Harbin subway SR-GPA assessment index system, analyzed the Harbin subway SR-GPA status, and proposed promotion strategies to improve the sustainability and resilience of Harbin subway.

Further conclusions can be drawn as follows: (1) sustainability and resilience are two important properties of urban infrastructure. Although these two concepts have different origins and independent developing routes in urban infrastructure, they share common connotations that are mainly reflected through research perspective, dimensions, methods, and goals. The concepts of sustainability and resilience should be integrated to provide a comprehensive assessment of urban infrastructure's property. (2) The biggest challenge for assessing properties of urban infrastructure's sustainability and resilience is how to combine the two concepts. Urban infrastructure SR-GPA is a new conceptual attempt to provide a unified perspective of urban infrastructure's sustainability and resilience. Urban infrastructure SR-GPA can be divided into basic quality and expanding quality, which reflect urban infrastructure's sustainability and resilience, respectively. (3) The assessment of urban infrastructure SR-GPA involves multiple dimensions and indexes, which constitute the assessment index system of urban infrastructure SR-GPA. The interactions of different dimensions and indexes should be considered in the assessment process, and ANP is a reasonable choice which can solve the above problem through the construction of the ANP structure model. (4) The empirical study of the Harbin subway shows that the proposed method can locate dimensions that are important for improving urban infrastructure SR-GPA. The weights of influence and measure dimension are relatively large. These indexes should be focused in the process of improving urban infrastructure SR-GPA. The weights of demand dimension are relatively small, which reflects that urban development level has small impacts on urban infrastructure SR-GPA. (5) The Harbin subway SR-GPA is in a relatively low level and needs to be upgraded through increasing construction investment, allocating resources efficiently and considering resilience in whole life cycle. The assessment results of the Harbin subway SR-GPA can be used to guide the future construction and operation of the Harbin subway.

Future works can be done to improve the assessment index system of urban infrastructure SR-GPA. More indexes should be selected and added to reflect the resilience of urban infrastructure. The automatic assessment system of urban infrastructure SR-GPA can be developed to provide the real-time data of urban infrastructure SR-GPA.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Public-Private Partnerships in the Electric Vehicle Charging Infrastructure in China: An Illustrative Case Study

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Effective supply of charging infrastructure is a necessary support for the development of electric vehicle and also an important strategic measure to promote energy consumption revolution and green development. The construction and operation of charging infrastructure in China is unfortunately not smooth, lagging behind the actual demand. Public-Private Partnerships (PPPs) may offer a promising way forward and accelerate the development of charging infrastructure by tapping the private sectors' financial resources and professional skills. However, PPP has not been commonly adopted in this sector yet. This paper hence studied an illustrative case of Anqing Project in China to demonstrate how governments structure a PPP deal in the electric vehicle charging infrastructures. A content analysis was conducted on the important project documents to investigate key elements including the planning, construction, risk sharing, profit distribution, and supervision during the execution stage. Based on the illustration, some key lessons and recommendations were provided to offer a reference for future charging infrastructure PPP projects in China.

1. Introduction

China's newly developed urban electric vehicle charging infrastructure provides power through high-voltage centralized charging stations and low-voltage decentralized charging piles. This infrastructure is an important baseline for the popularization of electric vehicles, whose development and adoption can accelerate the replacement of fossil fuels and reduce automotive exhaust emissions, helping to ensure energy security, promote emissions reduction, and prevent air pollution. The promotion of charging infrastructure in China is therefore an urgent strategic measure underlying the energy consumption revolution and green development.

As of the end of 2016, China had nearly 150,000 public charging piles, more than twice the number in 2015, making China a global leader in developing charging infrastructure [1]. Although charging infrastructure in China is large in absolute terms, it lags well behind the rate of electric vehicle development (Figure 1). The electric vehicles in proportion to charging infrastructure in Figure 1 refer to the number of electric vehicles sharing a public charging pile. This ratio is important for decision-makers to determine the number of public charging piles to be built according to the existing and expected numbers of electric vehicles. It also influences the customers' willingness to purchase and use electric vehicles. To the best knowledge of the authors, there is no universally accepted threshold value of the ratio. Given the strong strategic promotion of using electric vehicles, the Chinese government stated a goal of constructing 500,000 new public charging piles from 2015 to 2020, which however remains far from being achieved. The lack of charging infrastructure is considered a significant barrier for the wide acceptance of electric vehicles [2]. Being a quasipublic good, the initial investment from the government is large but insufficient, so a strong inflow of private capital is required [3].

Public-Private Partnership (PPP) is a long-term contract between a public party and a private party, for the development

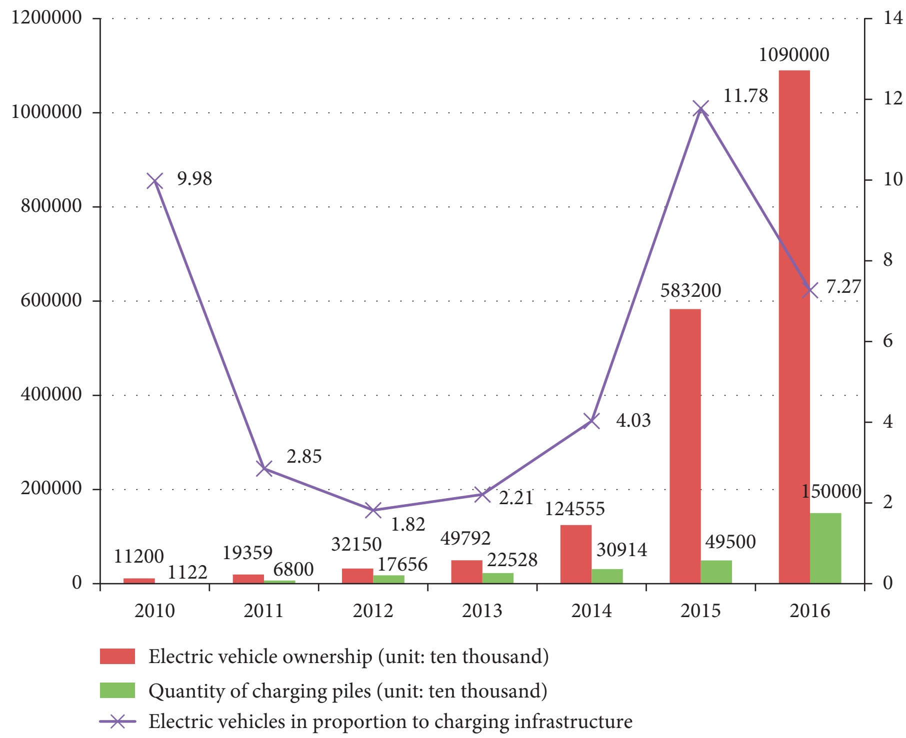

Figure 1: Electric vehicles in proportion to charging infrastructure in 2010–2016.

and management of a public asset or service, in which the private party bears significant risk and management responsibility through the life of the contract [4]. PPP may offer a promising way forward and accelerate the development of charging infrastructure by tapping the private sectors' financial resources and professional skills. However, PPP has not been commonly adopted in this sector in China yet. In the project database with a size of 14,424 projects operated by the Ministry of Finance (MOF) as of December 31, 2017, there were only 14 electric vehicle charging infrastructure PPP projects, of which three were procured [5]. It is not clear how the government should structure a PPP deal in the electric vehicle charging infrastructure to achieve value for money due to its significant differences with other infrastructure sectors such as transport, water, waste, and gas where it is common to see examples of PPP implementations. This paper hence aims to analyze the deal structure of an electric vehicle charging infrastructure PPP project, investigate key elements during the execution stage, and obtain key lessons and recommendations. By providing practitioners and academics with a better understanding of the differences between electric vehicle charging infrastructure PPPs and other PPPs, this paper expects to offer a reference for future charging infrastructure PPP projects.

2. Literature Review

2.1. Electric Vehicle Charging Infrastructure in China. Public charging infrastructure is a key to growing the electric vehicle market. In recent years, the central government has issued several relevant policies to support the construction of the electric vehicle charging infrastructure, such as Guiding Opinions on Accelerating the Electric Vehicle Charging Infrastructure Construction issued by the General Office of the State Council in October 2015 and Guidelines on Development of the Electric Vehicle Charging Infrastructure (2015–2020) issued by the National Development and Reform Commission in November 2015. These government documents are constituted to demonstrate the administrative processes for land acquisition, public funding, approvals, business operation, and so on. The charging infrastructure being developed in China includes centralized charging stations and decentralized charging piles at public charging stations, as well as public charging piles and private charging piles in public transportation, sanitation, rental, engineering, logistics, and other areas [3].

The numbers of charging piles and stations have increased but their growth has not matched that of electric vehicles (as shown in Figure 1). Because the gap between supply and demand of charging infrastructure is broadening increasingly, the charging infrastructure industry must undergo an explosive growth, which has been reflected in the government's strategic plan. According to the requirements in the Guidelines on Electric Vehicles Charging Infrastructure Development (2015–2020), the number of charging piles and stations should exceed 4.8 million and 12,000 by 2020, respectively, which are 154 times and 15 times the existing levels. The investment demand window in the charging infrastructure will hence be opened.

Compared to other infrastructure sectors, electric vehicle charging infrastructure has the following unique characteristics: it requires a large initial investment as well as a long-term operation and maintenance investment [3]; it requires a strong coordination with the smart city planning, power grids, and an intelligent transportation layout, which involves multiple stakeholders, high complexity, and difficulties with promotion [6]; it is exposed to various risks including changes in policies, business default, technical risks, security, market uncertainty, price adjustment risks and so on [7]; the technological advances such as battery production and electricity storage technology, wireless payment, and management are updated constantly [8].

2.2. International Practices in Electric Vehicle Charging Infrastructure. Along with the promotion of electric vehicles, many governments at both national and local levels have recognized the importance of charging infrastructure and proposed different development programs. However, these programs vary widely in scope and focus. Hall and Lutsey summarized the international practices in developing electric vehicle charging infrastructure [9], which indicates the fact that PPP is not commonly adopted in this specific sector internationally. Because electric vehicle charging infrastructure is not necessarily the responsivity of governments, governments and private companies have both been constructing public charging infrastructure for several years in many countries. In addition, all recommendations must naturally be tailored to fit local political, geographic, and demographic contexts for each country. Therefore, international practices of charging infrastructure PPP projects are not selected to study in this paper because of the research purpose.

2.3. PPP Implementations in China. PPP has been extensively used to deliver an array of infrastructure projects in China since 1980s. Cheng et al. divided the development history of PPPs in China into four phases based on the national macroeconomic environment, relevant milestone policies, and statistical analysis of their self-collected database, that is, phase one—exploration (1984–2002), phase two—stable expansion (2003–2008), phase three—development with fluctuations (2009–2013), and phase four—new boom (end of 2013 to current) [10]. In phase one, PPP was mainly applied in transportation, energy, water, and waste treatment sectors; the main player was foreign investors with mature technologies and management skills; Build-Operate-Transfer (BOT) was the most common contract type. In phase two, PPP was applied mainly in municipal utilities, such as water supply, sewage treatment, garbage disposal, and heat supply; state-owned companies and private investors took the leading role while foreign investment declined its share significantly. In phase three, state-owned companies absolutely dominated the PPP market given the fact that they possessed more government resources, by being highly affinitive with local governments and more favored by state-owned commercial banks. In phase four, China is catching a PPP fever due to the strong promotion by the central government. The PPP environment has been improved significantly, including a PPP project database established by the MOF, a PPP center formed under the MOF, a series of rules and regulations issued to clarify issues like value for money, public affordability, information disclosure, and hundreds of national PPP demonstration projects to illustrate the best practices.

2.4. PPPs in Electric Vehicle Charging Infrastructure in China. The revenue from end-users cannot cover the construction and operation costs in a charging infrastructure project. In order to deliver such a project via PPP mode, a government fund is needed to close the investment gap [3, 11]. Therefore, compared to other economic infrastructure sectors such as power, toll road, and water, the charging infrastructure was not favored by both the public and private sectors. Along with the rapid development of PPPs since 2013, subnational governments started to explore the opportunity of using PPPs in many other sectors including the charging infrastructure. Currently, PPP in charging infrastructure in China is at its initial stage, in which the governments are enthusiastic, and the participation degree of private sector is increasing [7, 12]. Therefore, the planning, construction, risk sharing, profit distribution, and supervision during the execution stage need to be further studied. As of December 31, 2017, among the total 14,424 projects accounting for 18.2 trillion yuan in the project database operated by the MOF, there were only 14 electric vehicle charging infrastructure PPP projects, representing only 0.097% of the total project number and 0.027% of the total investment amount. Among the 14 projects, three projects have been procured, three projects have been approved and are being prepared for procurement, and the rest are still at the project identification stage. Table 1 summarizes the six approved electric vehicle charging infrastructure PPP projects. The payment mechanism of viability gap funding denotes that the government will make PPP projects financially viable by dedicating a portion of its budget to fund the gap between the expected project revenues and costs.

3. Research Methodology

The PPP model will be increasingly applied to the development of the electric vehicle charging infrastructure in China. But so far, only three PPP projects have been procured. To the best of the authors' knowledge, little effort has been seen in the research of PPP application in this sector. Therefore, it is urgent to know what the lessons are in the few existing projects, and a qualitative case study approach will be appropriate for the research purpose. According to Eisenhardt and Graebner and Yin, a case study is appropriate when existing theories or the available data are insufficient to engage in quantitative hypothesis testing and when the researcher desires to gain an in-depth understanding of a complex phenomenon within its specific context [13, 14].

As shown in Table 1, there are six approved electric vehicle charging infrastructure PPP projects in China, of which three are still being prepared for procurement and are hence excluded first. The Kaili project, the Anqing project, and the Liupanshui project were procured in March 2015, June 2016, and July 2017, respectively. Because most information of the Liupanshui project has not been disclosed yet (and will be disclosed within six months after its execution stage according to the MOF project database), and most information of the Kaili project is not available (and may not disclosed as no disclosure plan is given in the MOF project database), the Anqing project has the richest public-available information

Table 1: Overview of the existing charging infrastructure PPP projects.

Project name	Current stage	Launch time	Investment amount (million yuan)/(million US dollars)	Concession period (years)	Modalities	Scope of work	Payment mechanism
(1) Anqing electric vehicle charging infrastructure project	Procured	01-2016	818/124.58	13	Regional concession	Public charging piles: 1700 Bus charging stations: 4 (100 dc charging piles) (short-term)	Viability gap funding
(2) Liupanshui electric vehicle charging infrastructure project	Procured	03-2016	210.92/32.23	20	BOOT	Public charging piles: 396	Viability gap funding
(3) Kaili electric vehicle charging station project	Procured	03-2015	104/16.64	20	Not clear	Big charging stations: 12 Small charging stations: 100	
(4) Tianjin electric vehicle charging infrastructure project	Prepared	10-2014	516/76.08	20	BOT	Public charging piles: 2000 Bus charging stations: 40	Viability gap funding
(5) Kuerle electric vehicle charging station project	Prepared	11-2015	227.73/51.80	30	BOT	Distributed charging piles: 492 Integrated charging stations: 16	User pay
(6) Quanzhou electric bus and charging station project	Prepared	09-2017	78.00/11.95	10	Regional concession	Electric bus: 120 Integrated charging stations: 1	Government pay

Note: this table shows only projects that are at procured and prepared stage, and projects in the identification stage are not included because of too little information.

and was selected for a single case study in this paper. Moreover, the Anqing project is one of the national demonstration projects, which reinforces the rationality of studying this project to achieve the research purpose. National PPP demonstration projects are selected by the MOF to highlight key examples of best practice in PPP implementations in order to further promote PPP to a larger scale. As of December 2017, there are 697 national PPP demonstration projects.

Due to limited information, a single case study method was adopted in this paper. In particular, the purpose of the study is illustrative. It is expected to demonstrate how the Chinese government structured the deal in the Anqing project, with a closer look at some key elements including the planning, construction, risk sharing, profit distribution, and supervision during the execution stage. All information and data of the Anqing project are mainly derived from important project documents including value for money report, fiscal affordability report, feasibility report, procurement documents, and PPP agreement in the PPP project database established and operated by the MOF.

4. Case Study: the Anqing Charging Infrastructure PPP Project

4.1. Project Background. The Anqing project, located in Anqing, Anhui province, the largest charging infrastructure PPP project executed in China, was formally signed in June 2016, later becoming a national demonstration project. It would be carried out in two phases. The first phase covers 103 square kilometers of the main city, and the second phase covers one town (Tongcheng) and six rural suburbs (Susong, Huaining, Qianshan, Yuexi, Taihu, and Wangjiang) under the jurisdiction of Anqing. By 2020, nearly 20,000 public charging piles will be built. The goal of the project is to provide public charging infrastructure and services using a smart service platform. A consortium led by Qingdao TGOOD Electric Co., Ltd., a private enterprise, was awarded the project through a competitive consultation. The private consortium is responsible for the financing, design, construction, operation, and maintenance. The payment mechanism is the method of viability gap funding, meaning that the project revenues are from user charges, and the government will dedicate its budget to fund the gap between the expected project revenues and costs. A Special Purpose Vehicle (SPV, a project company created to develop and manage the project, which is a key feature of most PPPs) was configured, in which the government's agency and private consortium hold 10% and 90% shares, respectively. The project's transaction structure is shown in Figure 2.

4.2. Project Planning. The network effect of the planning is significant. Broadly available public charging infrastructure can meet the mobility and diversity requirements of electric vehicles [11], thereby promoting the usage of electric vehicles that in turn will increase the usage of charging service [15]. In addition, the economy of scale in the electric vehicle charging service industry is apparent. In order to reduce overall operation and maintenance costs, a specific modality

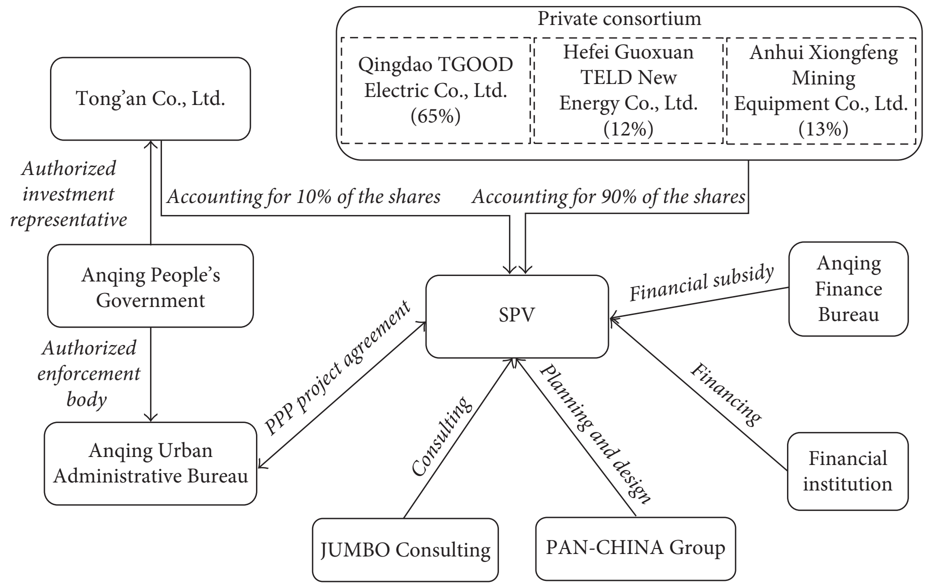

Figure 2: Project transaction structure.

of regional concession was adopted in the Anqing project. The private consortium was offered the exclusive concession right to build and operate the charging infrastructure within the defined area (i.e., 103 square kilometers of the main city, one town, and six rural suburbs). In a typical BOT project, the exclusive right is only applied to the BOT project itself with a promise of limiting competition. In this project, the exclusive right is applied to the whole defined region with a promise of not building any charging infrastructure.

Since the electric vehicles and the relevant charging infrastructure service are still under development in Anqing, it is difficult to accurately forecast the demand. Therefore, a short-term dynamic adjustment of work scope was introduced in the PPP contract of the Anqing project, which initially specified the goal of construction in 2016 being 1800 charging piles (1000 public charging piles in the main city, 100 charging piles for four bus charging stations, and 700 charging piles in one town and six rural suburbs). The construction plan for the following years during the concession period will be separately formulated and submitted to the government for implementation.

As an integral part of the future urban infrastructure system, charging infrastructure planning must be effectively coordinated with other infrastructure planning (such as electricity, transportation, informationization, etc.). At the preliminary expert review meeting for the special plan of new energy electric vehicle charging infrastructure in Anqing, electrical engineers, urban planners, and staff from the municipal planning bureau, traffic police detachment, power supply company, and other government departments were invited to participate in the joint coordination of planning. Meanwhile, the SPV was required to build an independent smart charging service platform for the project to ensure that the platform would be interconnected with the digital urban management platform of Anqing and reserve data interfaces for other provincial and national management platforms.

4.3. Construction Arrangement. Due to the requirements of abovementioned network effect and economy of scale, the construction was required to be systematically planned and optimally placed. In particular, the SPV was required to use charging equipment complying with "Connecting Device for Electric Vehicle Conduction Charging-Part 1: General requirements" (GB/T 20234.1-2015), "Connecting Device for Electric Vehicle Conduction Charging-Part 2: the AC Charging Interface" (GB/T 20234.2-2015), "Connecting Device for Electric Vehicle Conduction Charging-Part 3: the DC Charging Interface" (GB/T 20234.3-2015), and other relevant national standards. In addition, the construction of a smart charging service platform and its connection with the Anqing digital urban management platform, provincial, and national management platforms was emphasized.

One of the challenges in the construction phase lies on the decentralized construction sites, which not only caused difficulties in construction management but also resulted in the difficulties in land acquisition. There are mainly three types of construction lands in the Anqing project: (1) to build charging piles in existing private car parks, the SPV should negotiate with the land-use right holders in a market-cooperative manner with an endorsement from the government; (2) to build charging piles in existing public transport stations, the SPV should rent the land from its land-use right holders; (3) to build centralized public charging infrastructure on an independent site, Anqing Urban Administrative Bureau will coordinate the relevant departments to supply the land through an open competition process.

4.4. Risk Sharing. Major risks of the Anqing project were divided into seven categories: design/construction, operation, financial, revenue, legal, government behavior, and others. Table 2 summarizes the risk allocation between the public and private sectors. In the following paragraphs, some

Table 2: Risk allocation in the Anqing project.

Risk category	Government	SPV
Design/construction risk		
Planning and site selection risk	√	
Land delivery and coordination risk	√	
Design faults		√
Engineering technical faults		√
Labor and equipment acquisition		√
Expansion of power supply capacity		√
Construction preparation		√
General engineering variation		√
Cost overruns of construction and procurement		√
Completion risk		√
Site safety, environmental protection		√
Operation risk		
Facilities' technical defects		√
Commissioning test		√
Facilities and equipment failure		√
Cost overruns of operation and maintenance		√
Quality of service do not reach the standard		√
Grid load regulation		√
Operator default and early termination		√
Overhaul and asset replacement		√
Safety management in operation period		√
Environmental protection in operation period		√
Financial risk		
Financing failure		√
High financing costs		√
Interest rate change		√
Foreign exchange risk		√
Debt risk/liquidity risk		√
SPV bankruptcy	√	√
Revenue risk		
Change of electric car ownership/charging infrastructure utilization ratio	√	√
Government pricing changes, such as service fees	√	
Changes in other revenue		√
Inflation	√	√
Legal risk		
Contract document conflict	√	√
Third party default		√
Government behavior risk		
Government default and early termination	√	
Expropriation and nationalization	√	
Approval delay	√	
Special engineering variation	√	
Tax variation	√	√
Industry standard variation	√	√
Technology variation	√	√
Other risk		
Force majeure	√	√

unique risks for electric vehicle charging infrastructure projects are further explained.

4.4.1. Design/Construction Risks. The placement of charging infrastructure is an important consideration because many issues need to be addressed, including charging time, distribution, demand policies, and design standardization [16]. At present, the development of vehicles and infrastructure is not coordinated, leading to the contradictory occurrences of inconvenient charging and idle charging piles, resulting in wasted resources and low operational efficiency. Meanwhile, a large-scale unbalanced placement can have a detrimental impact on the electric grid, resulting in a significant operational risk.

Because the public charging demand is mainly located in mature central urban areas, the construction of charging infrastructure will encounter problems of demolition, property ownership, and more, such that the redevelopment cost of land is high. Meanwhile, the existing electric infrastructure may not be adequately designed to satisfy the surge in power demand necessary for increased electric service infrastructure in these areas [17], resulting in increased distribution transformer losses, voltage deviations, harmonic distortion, and peak demand [18]. The central areas of large cities in China have limited resources and so the potential for power tapping is limited. The expansion of power facilities, such as wires, transformers, and electric meters will pose a challenge to the regional power load.

4.4.2. Operational Risks. Table 2 shows all operational risks that are borne by the SPV in the Anqing project, which are the most important risks in this type of project. In the operation of charging infrastructure, factors such as cost control, efficiency improvement, charging time, and adjustments to usage demands would cause extra difficulties to operation management. Equipment replacement through technical upgrades, distribution equipment overloads caused by power demand surges, increased distribution transformer losses, voltage deviations, and harmonic distortions are some common operational risks in charging infrastructure projects [17–19].

4.4.3. Revenue Risks. According to the press, most charging infrastructure investments in China have faced losses or low returns from 2006 to 2014 [20]. The Anqing government encouraged the SPV in the PPP agreement to participate in special charging infrastructure investment, construction, and operation at residential areas or workplaces within the planning area to increase its revenue. At present, the charging price of electric vehicles in China includes two parts: the charging service fee and the electricity fee. In the Anqing project, the fees charged by the SPV are set by the government, and the SPV has no control authority on the changes of fees. Therefore, the risk of pricing changes is allocated to the government.

4.4.4. Technical Risks. Technical risks in charging infrastructure project are high. Continuous changes in technology may lead to the replacement of existing charging equipment, or even alternative technical methods, which would cause a significant additional investment. Therefore, technical risks are shared by both parties in this project.

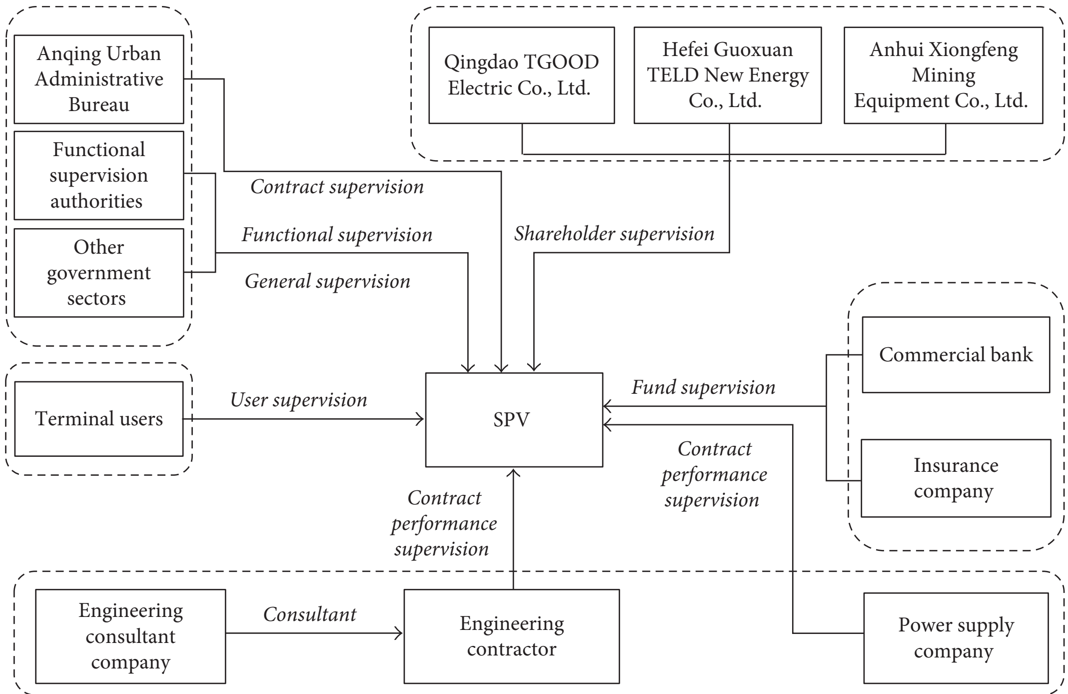

Figure 3: Supervision framework of the Anqing project.

4.5. Profit Distribution. In the Anqing project, the payment mechanism is the viability gap funding, including user charges and viability gap funding from the government. The former includes the electricity fee and charging service fee. During the operation period, the electricity fee is charged according to the "notice on the price of charging service for electric vehicles in Anqing" [21]. If electricity prices are changed, new prices will be adopted. The charging service fee is based on the government guidance price prior to 2020, after which it will be determined in accordance with relevant laws and policies, and through discussions with the SPV.

The viability gap funding consists of two parts: the availability and operation/maintenance subsidies. The availability subsidy is subject to the amount of construction investment and operation revenues, as well as the annual comprehensive performance assessment score. If the score is ≥85 points, the subsidy will be paid in full; if the score is <85 and ≥70 points, the subsidy will be reduced to 85%; if the score is <70 points, the subsidy will be reduced to 70%. The operation/maintenance subsidy aims to fill the gap between operational costs and revenues from the electricity and charging service fees. The Anqing PPP contract defines the following:

(1) When the charging pile utilization rate is high, meaning that the ratio of actual charging usage to expected usage is >85% and <115% and the project income is not enough to cover costs, the government will fully compensate for the gap; if the income is greater than cost, the government will provide no subsidy, nor will it share the excess profit.

(2) When the charging pile utilization rate is low, meaning that the ratio of actual charging usage to expected usage is <85% and the project income is not enough to cover costs, the government will compensate 85% of the gap (thus embodying risk sharing); if the income is greater than the cost, government will provide no subsidy, nor will it share the excess profit.

(3) When the charging pile utilization rate is extremely high, meaning that the ratio of actual charging usage to expected usage is >115% and project income is not enough to cover its costs, the government will fully compensate for the gap; if the income is greater than the cost, but the ratio of income to cost is not higher than 110%, the government will not provide a subsidy, nor will it share the excess profit. However, if the ratio of income to cost is higher than 110%, the government will obtain 10% of the net yield.

4.6. Supervision. Figure 3 presents the overall supervision framework for the Anqing project. The government agencies involved and supervision methods will be further explained below.

4.6.1. Government Agencies. Stakeholders involved in the supervision of the Anqing project are comprised of relevant government agencies, contracting parties, and the public (mainly the users). The government agencies include the following:

(i) Procuring authority: Anqing Urban Administrative Bureau, which signed the PPP project agreement with the SPV, will supervise and manage the investment, construction, and operation of the project.

(ii) Functional authorities: Anqing Development and Reform Commission, Housing and Urban-Rural Construction Committee, and Finance Bureau at all levels will supervise and manage within their respective institutional responsibilities.

(iii) Other government authorities: Electric Power Bureau, Administration of Industry and Commerce, and Public Security Bureau will supervise and manage according to their respective institutional functions and responsibilities. These agencies are less relevant to the deal structure of the Anqing project.

4.6.2. Supervision Methods. The contract management (including performance monitoring) from the procuring authority and other contracting parties, administrative supervision (including approvals) from functional government agencies and other relevant agencies, and public supervision from the general public, and more importantly end-users are the main supervision methods. These methods jointly provide an efficient and effective framework to ensure that the project achieves the expectations. During the project design and construction stages, administrative supervision dominates. It ensures that the correct processes are followed, that analysis of the proposed PPP is complete, that all the agencies that need to comment or give their approvals do so, and that the approval authorities receive all the information they need to make a sound decision. During the operation phase, one of the key activities in managing the PPP contract is to monitor project delivery and performance against output specifications. Performance monitoring and management hence performs the leading role. At this stage, public supervision also plays an important role in receiving feedback from end-users and general public for the SPV to continuously improve their charging service.

5. Discussions

Although the PPP model has not been widely used in the realm of charging infrastructure, the potential is great. First, compared to the traditional energy sector that is relatively monopolistic, electric vehicle charging infrastructure is a new energy industry and has fewer regulatory restraints. Second, of the fourteen PPP projects that have been identified in the PPP project database, most projects did not use government-pay mechanism. PPP is hence favored by local governments suffering severe financial burden. Moreover, the demand of charging infrastructure has been well validated along with the rapid development of electric vehicle market. On the other side, the limited implementation of PPPs in the charging infrastructure to date results in a concern of how the government should structure an electric vehicle charging infrastructure PPP project, which has been partly solved by the abovementioned illustrative case study of the Anqing project. In this section, some key lessons and recommendations are further discussed to provide a reference for future charging infrastructure PPP projects in China.

5.1. Planning a Coordinated and Dynamic Development. The planning of charging infrastructure PPP projects must take into account the network effect and the impact of economies of scale. With the continuous expansion of electric vehicle usage, the layout of charging stations and charging piles need to be optimized using a system optimization perspective and integrated in accordance with the electricity demand characteristics of mobility, diversity, and bootability. An integrated information management platform is often required to construct an efficient, intelligent, and standardized charging service network.

Electric vehicle utilization rates, user charging convenience, land supply, and other factors should be considered in the planning of site selection and quantity arrangement processes for the charging infrastructure. A scientific and systematic planning can no doubt improve the utilization of charging infrastructure, which should also be coordinated with the overall city planning, road network, and power grids. This would reduce impacts of travels for the purpose of charging on the city traffic, ensure that the power grids provide adequate power for electric vehicles, and avoid voltage limits or overloading power distribution lines/equipment.

In addition, charging infrastructure planning should adequately consider uncertainties in the initial period and adapt to the frequent updates of electric vehicle technology. The planning decision of work scope should be careful in order to avoid idleness and resource waste. The interaction between promoting electric vehicles and constructing charging facilities should be also fully considered.

5.2. Constructing with Unified Standards and Reducing Construction Costs. The unified standards related to charging infrastructure are requisite for ensuring the proper construction of charging facilities, charging safety, vehicle-pile interconnection, and payment interoperability and information exchange. In December 2015, five government departments including the National Energy Administration of China, jointly issued five newly revised national standards for electric vehicle charging interfaces and communication protocols. The levels of standards include the national standards (GB/T), industry standards (NB/T), and professional association standards (T/CEC). The content of standards covers charging interface and communication protocol, charging facilities and key equipment, charging station construction, power exchange, charging facilities operation and maintenance, operation monitoring and operation platform communication, and symbol standards. The construction of charging infrastructure must comply with these unified standards to enhance the interoperability for both the electric vehicle drivers and the SPV.

As shown in the Anqing project, the construction sites of a charging infrastructure PPP project are often scattered and located in existing buildings and stations. The construction costs are likely to increase due to the difficult coordination among different construction sites and with different stakeholders. However, existing urban infrastructures may provide an opportunity to reduce the construction cost if policies to streamline the construction of charging infrastructure in existing buildings are in place and the existing urban infrastructure can be transformed to provide charging service. For example, the transformation of street lights into charging facilities in Germany could save about 90% of the construction cost [1]. Therefore, opportunities for cost reduction should be carefully examined through innovative technical solutions.

5.3. Identifying Project Risks Comprehensively and Sharing Them Properly. PPP projects confront great risks due to their multiple participants with different objectives and interests. Therefore, the ultimate project success can only be realized when the risks have been comprehensively identified and properly shared. The Anqing project is not an exception. As presented in Table 2, the most significant risks are associated with the operation of the project. This is because most risk factors are likely to result in issues occurring at the operation stage. Due to the unique characteristics of electric vehicle charging infrastructure, such as a rapid development in recent years and frequent updates of technical solutions, the government is committed to sharing technical risks and revenue risks in the Anqing project through the contractual arrangements of a dynamic scope of work and payment mechanism, respectively.

5.4. Building a Smart Service Platform to Provide Diversified Services. In the Anqing project, the SPV attached great importance to the simultaneous construction of smart service charging platform and its connections with other municipal and provincial/national platforms, so that the SPV will be able to provide customers with charging navigation, status inquiries, charging reservations, cost settlement, used car trading, car washes, and other services to increase revenues.

One of the characteristics of the Anqing charging infrastructure service platform is the strong Internet connectivity, which can significantly reduce the queuing time and strengthen third party resource integration capabilities through providing live information of charging infrastructure on the Internet. Commercial value-added space will be expanded while providing convenient services for users. The private sector needs to develop a smart service platform to record the big data of customers and analyze the data to solve the operation problems and seek for new value-added business opportunities.

5.5. Strengthening Project Supervision. The government needs to ensure the selection of right private partners that is a key to the project success. The selection criteria should include but not be limited to rich experience, strong technical, financial, and management capacity. In the Anqing project, the government emphasized technological capacity in the charging equipment supply, construction, and operation. TGOOD, the leader of the private consortium, is a Sino-German joint venture company, with a strong financial capability and a comprehensive technical capacity and rich experience in the whole industrial chain, including charging equipment supply, construction, and operation.

Furthermore, the supervision of the PPP life-cycle processes also needs to be strengthened. The charging infrastructure is not completed by a short-term centralized construction effort but is gradually expanded and improved according to the market development. Its scale is in accordance with an appropriate proportion to the overall number of electric vehicles, while construction and operation are often carried out simultaneously. Therefore, the supervision of the life-cycle process is very important, which is not only related to the quality and standard of the service provided by the project, but also related to the calculation of the subsidy for the viability gap of SPV. Thus, in the entire project concession period, performance monitoring and management (including construction performance assessment and operation performance assessment) is often involved.

6. Conclusions and Future Research

Charging infrastructure is an important baseline for the popularization of electric vehicles, while the introduction of PPP to this sector is conducive to the government's use of private resources by increasing the supply of and optimizing the use of charging services. However, PPP has not been commonly adopted in charging infrastructure in China. It is not clear how the government should structure a PPP deal in the electric vehicle charging infrastructure to achieve value for money due to its significant differences with other infrastructure sectors. In this paper, an illustrative case study of the Anqing project was conducted to investigate key elements including project planning, construction arrangement, risk sharing, profit distribution, and supervision during the execution stage. Based on the illustration, some key lessons and recommendations were provided to offer a reference for future charging infrastructure PPP projects, including planning a coordinated and dynamic development, constructing with unified standards and reducing construction costs, identifying project risks comprehensively and sharing them properly, building a smart service platform to provide diversified services, and strengthening project supervision. The case study can provide industry practitioners with a clear guidance of structuring a PPP project because this project has been carefully evaluated through the MOF process to be nominated as one of the national demonstration projects and is hence a good practice for the industry to learn and follow.

At present, PPP in charging infrastructure in China is at the initial stage; government sectors are enthusiastic but private investors' willingness still needs to be stimulated. As one single case study was conducted in this paper, the findings may be biased and need to be carefully examined before being applied to future PPP implementations. Due to the limited access and timeframe, interviews cannot be conducted to collect first-hand data. Therefore, more similar projects can be studied in the future, especially on the topics of how to make a coordinated and dynamic plan, methods to reduce execution costs, and risk management. In addition, because the selected case has been procured only for less than two years, the operation performance still remains unclear, which leads to another future research opportunity to review the project at a later stage.

Data Availability

Raw data were generated at the PPP Project Library operated by Ministry of Finance, China (http://jrs.mof.gov.cn/ppp/). Derived data supporting the findings of this study are available from the corresponding author on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

A Flexible Bridge Rating Method Based on Analytical Evidential Reasoning and Monte Carlo Simulation

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Several bridge inspection standards and condition assessment practices have been developed around the globe. Some practices employ four linguistic expressions to rate bridge elements while other practices use five or six, or adopt numerical ratings such as 1 to 9. This research introduces a condition rating method that can operate under different condition assessment practices and account for uncertainties in condition assessment by means of the Evidential Reasoning (ER) theory. The method offers flexibility in terms of using default elements and their weights or selecting alternative set of elements and condition rating schemes. The implemented ER approach accounts for uncertainties in condition rating by treating the condition assessments as probabilistic grades rather than numerical values. The ER approach requires the assignment of initial basic beliefs or probabilities, and typically these initial beliefs are assigned by an expert. Alternatively, this research integrates the Monte Carlo Simulation (MCS) technique with the ER theory to quantitatively estimate the basic probabilities and to produce robust overall bridge condition ratings. The proposed method is novel to the literature and has the following features: (1) flexible and can be used with any number of bridge elements and any standard of condition grades; (2) intuitive and simple paired comparison technique is implemented to evaluate weights of the bridge elements; (3) the MCS technique is integrated with the ER approach to quantify uncertainties associated with the stochastic nature of the bridge deterioration process; (4) the method can function with limited data and can incorporate new evidence to update the condition rating; (5) the final rating consists of multiple condition grades and is produced as a distributed probabilistic assessment reflecting the condition of the bridge elements collectively. The proposed method is illustrated with a real case study, and potential future research work is identified.

1. Introduction

Transportation bridges are critical to cities and societies as they facilitate movement of people and goods on daily basis. Bridge infrastructure is aging and deteriorating and requires attention either immediately or on the short term [1, 2]. To address bridge infrastructure needs, several countries around the world developed and used bridge management systems (BMSs) to store and analyse bridge inventory data and to support the bridge management decision-making process in relation to budget allocation and the selection of efficient maintenance, repair, and replacement (MR&R) interventions. The most important requirement of any BMS is the bridge condition assessment and rating module since condition rating relates directly to safety and serviceability of the structure.

Existing bridges are evaluated by either conducting an analytical evaluation of the load-carrying capacity or performing a visual inspection to rate the condition of the bridge elements. The analytical approach evaluates bridge elements load resistance compared to the applied service loads. The analytical evaluation and rating procedures are documented in codes of practice such as AASHTO LRFD [3], CAN/CSA-S6-14 [4], and ENV 1991-3 Eurocode 1 [5]. The other practices in bridge condition assessment are typically based on the bridge visual inspection process, during which experienced inspectors visit the bridge site to assess the condition of the various elements and assign subjective rating to each element based on extent and severity of identified defects and deterioration.

Several inspection manuals and condition assessment standards are developed by the various departments of transportation around the globe to regularize the bridge inspection and condition assessment process. These references provide procedures and guidelines to assist bridge inspectors in conducting the inspection and collecting the needed data. In addition, they include guidelines to assist in rating the bridge elements. Among these standards are the ones introduced by the Federal Highway Administration (FHWA) to manage bridges in the United States, including the National Bridge Inventory (NBI) and the National Bridge Inspection Standards [6]. The ministry of transportation of Ontario, Canada, developed the Ontario Structure Inspection Manual [7]. It provides descriptions and details of standard inspection procedures. In Europe, several projects had been undertaken to develop bridge inspection and maintenance standards such as Bridge Management in Europe (BRIME), Contecvet, Lifecon, and Rehabcon [8]. Condition assessment and rating methods capable of capturing data collected during bridge inspection and producing robust condition ratings are paramount for the bridge management process.

This research paper introduces a flexible bridge condition assessment and rating method that accounts for uncertainties associated with the visual inspection process. The approach can function with the different bridge inspection standards and requirements and uses paired comparison technique to intuitively assign weights to bridge elements. The method integrates the Monte Carlo simulation (MCS) with the evidential reasoning (ER) approach to quantify uncertainties associated with bridge assessment and rating processes.

2. Literature Review

Several studies aimed at developing bridge rating methods. Methods for component and system reliability are among the approaches that received acceptance for bridge evaluation [9]. The main purpose of the reliability assessment is to determine the load-carrying capacity of a bridge through estimation of a reliability index β. The main goal of the reliability analysis is to assess the bridge safety and eventually supporting the bridge management decision-making process regarding maintenance, retrofitting, and replacement interventions. Nowak et al. [10] compared reliability of concrete bridge girders designed based on guidelines of three different codes of practice. Zonta et al. [11] proposed a systematic reliability-based bridge management approach to assist in managing bridges in Italy. Estes and Frangopol [12] reviewed limitations and necessary modifications to condition rating practices and presented a study on how to use available visual inspection data to update reliability of bridges. They applied the approach to a superstructure of a deteriorating bridge in Colorado. Ghodoosi et al. [13] proposed a reliability-based deterioration model and demonstrated how to update the reliability of bridges using ground penetrating radar data. Estes and Frangopol [12] discussed that the reliability methods are powerful for quantifying risk and uncertainty, but they require a large amount of input data to perform the analysis. They also pointed to the fact that nondestructive testing and ground truth condition are needed inputs to perform reliability analysis, but these data are not available for every bridge.

Other studies focused on developing condition rating methods using available bridge inspection data and addressing subjectivity and uncertainty associated with the bridge visual inspection process. Researchers used fuzzy logic to address subjectivity associated with the use of linguistic expressions typically used for rating bridge elements. Tee et al. [14] were the first to propose a fuzzy weighted average approach. They developed membership functions to depict fuzziness in linguistic rating expressions. The data for the membership functions were collected through a questionnaire survey distributed to bridge engineers and inspectors from the state of Indiana and the neighbouring states. Further research was built on the principles of the fuzzy weighted average approach and introduced the integration of multiattribute decision-making techniques and fuzzy logic to rate concrete bridges [15, 16]. A multilayer fuzzy synthesis assessment model to evaluate bridge damages was proposed in the literature. Five grades were selected for the multilayers: nondamage, light damage, moderate damage, severe damage, and unfit for service [17].

Artificial intelligence was investigated as a potential approach to enhance bridge condition assessment and condition rating. Li et al. [18] assessed the feasibility of using neural networks in bridge condition evaluation and proposed five subnets neural network for the deck, the superstructure, the substructure, the channel, and the overall evaluation. Cattan and Mohammadi [19] discussed that conventional statistical models and fuzzy-based methods were not successful in mapping between the subjective condition rating and the analytical evaluation of bridges. Alternatively, they used neural networks to map subjective ratings and bridge parameters and to compare subjective to analytical bridge ratings. Sobanjo [20] used neural networks to perform bridge condition rating. The network was trained to produce a condition rating based on inputting the age of a bridge in years. Case-based reasoning (CBR), a branch of artificial intelligence, was proposed in the literature to assess bridge deterioration and forecast future conditions. The underlying principle of the CBR is building a library of cases that can be used to solve a new problem if the new problem is similar to one of the cases in the database. Specific limitations of the CBR approach were identified, such as difficulties in retrieving similar cases especially if the library does not include sufficient cases, and complexity of developing a library of cases in a specific domain that can be used for case adaptation [21].

Wang and Elhag [22] reviewed fuzzy logic and neural network applications in bridge condition assessment and discussed that these approaches have limitations related to modelling uncertainties associated with the subjective ratings of bridge conditions. This can be attributed to the observation that fuzzy logic and neural networks may not provide a full description of the various levels of the overall assessment of a bridge structure. They discussed that the fuzzy inference model represents bridge condition rating and assumes that the condition ratings comply with the fuzzy number addition operation. In addition, the multilayer fuzzy synthesis assessment model requires bridge experts to subjectively assess each bridge element to single assessment grade with 100% confidence. They also discussed that the neural network models require significant amount of bridge inspection data to establish the mapping between inputs and outputs. Alternatively, Wang and Elhag [22] proposed the ER theory to model uncertainties inherent in bridge subjective assessments as an enhanced bridge condition assessment approach. The ER method produces distributed final overall assessment offering a panoramic view of the bridge condition ratings. They illustrated the ER method implementation with a hypothetical case study. Deng et al. [23] proposed the use of the D number with the ER method to perform bridge condition assessment and used Wang and Elhag's case study to demonstrate and validate their approach. Moufti et al. [24] proposed defect-based bridge condition assessment method based on the fuzzy hierarchal ER approach. They developed the needed membership functions based on defect severity levels defined by the Ministry of Transportation in Quebec.

Despite the significant effort to develop condition assessment and rating methods, further research is still needed. The literature review identified potential research areas that require further investigation, including (1) condition rating methods typically focus on one of the current practices in bridge condition assessment in term of selecting the assessment grades, choosing the breakdown of the bridge structure into elements, and selecting weights of these elements. A review of current practices (discussed in a later section) identified difficulties in standardizing bridge condition assessment process. In response, flexibility in condition assessment and rating methods needs to be enhanced; (2) the primary step in the ER method is defining the basic probability assignment (BPA). The BPA represents the confidence assigned to a certain proposition and reflects to what extent the existing evidence may support the proposition. The BPA values are usually assessed subjectively by an expert. A formal quantitative approach to estimate the BPA can enhance the process; and (3) the ER method uses either an analytical or a recursive algorithm to combine the various evidence. The literature lacks for studies to compare both algorithms performance when applied to bridge condition rating problem. This research proposes a flexible ER-based bridge condition rating method that attempt to address the above first and second limitations. Future work may expand on the current research to study and compare the performance of the analytical and the recursive algorithms.

3. Bridge Inspection and Condition Assessment

A thorough review of bridge inspection manuals shows that different countries in the world have implemented different bridge inspections and condition assessment guidelines. However, in principle, all these practices stem from the same method, which is the periodic visual inspection by well-trained teams of inspectors to assess conditions of the various bridge elements. Several initiatives in many countries in the world have been undertaken to develop and enhance bridge condition assessment practices. The FHWA established the National Bridge Inspection Standards to standardize the process and guide inspectors in reporting conditions of bridges on the public roadways [25]. The FHWA introduced a program to translate bridge condition data of commonly recognized bridge elements consistent with the National Bridge Inventory (NBI) condition ratings format [25]. The program helped the different states to report bridge inspection results to the NBI and enabled the use of the collected data in bridge management. The NBI rating system is based on a 0 to 9 scale to rate the elements while the final overall condition rating is reported in one of three categories: good, fair, and poor [3].

In Europe, a BMS known as BRIME (Bridge Management in Europe) was developed by the national highway research laboratories in the United Kingdom, France, Germany, Norway, Slovenia, and Spain [5]. The purpose of the project was to unify bridge management practices in these countries. Other European countries worked individually to set their bridge management standards. For instances, Denmark BMS uses bridge rating of 0–5 to describe bridge damage [26], and the Swedish Road Administration uses a rating scale of 0–3 to describe the condition of the bridge [27]. In Canada, the Ministry of Transportation in Ontario developed and used its own structure inspection manual [4]. The manual adopts a four-level rating system: excellent, good, fair, and poor. For each element within the bridge, the inspector assesses and records deteriorated quantities of the different elements as an area, length, or unit based on the geometry and nature of the inspected element. The assessments are mainly developed based on inspector's visual observations and the use of some nondestructive testing to identify and quantify the extent of deterioration and defects. Then, the elements conditions are aggregated into an overall condition rating of the bridge structure. Table 1 shows some of the current inspection manuals and refers to the publishing agency and the rating system adopted by each manual.

The different bridge management practices varied in identifying recognized sets of bridge elements for inspection purposes and the weights assigned to these elements also varied from one practice to another. The AASHTO Guide Manual for Bridge Element Inspection introduced a complete and flexible set of bridge elements as an attempt to satisfy needs of the different departments of transportation in the United States. These elements were designed to capture all the components necessary to manage the needs of the NBI and to facilitate the utilization of the BMSs developed by the departments of transportation [28]. The various states in America selected specific sets of elements to be considered in their BMSs and assigned weights to reflect the relative importance of the elements. For example, Wang and Elhag [22] referred to the 13 bridge elements used in New York BMS and the assigned the weights as shown in Table 2.

The FHWA reviewed the shortcomings of the NBI and started an initiative to standardize data collection. They developed a "Commonly Recognized (CoRe) Structural Elements" manual, which included definition of elements and

TABLE 1: Common North America and Europe bridge management systems with their bridge condition assessment.

Bridge management system (manual)	Publishing	Assessment grades (rating system)	Meanings of the rating system
National bridge inventory (NBI) [3]	US Department of Transportation	0–9	0: failed condition; 1: imminent failure condition; 2: critical condition; 3: serious condition; 4: poor condition; 5: fair condition; 6: satisfactory condition; 7: good condition; 8: very good condition; 9: excellent condition.
New York BMS [22]	New York Road Department	1–7	1: potentially hazardous; 3: serious deterioration; 5: minor deterioration; 7: excellent or new condition; 2, 4, and 6: between two adjacent ratings.
Bridge Ratings, Inspections and Records Manual (BRIAR) [27]	Department of Transportation, State of Colorado	Poor–Good	*Poor*: sufficiency rating less than 50 and status of structurally deficient or functionally obsolete. *Fair*: sufficiency rating from 50 to 80 and status of structurally deficient or functionally obsolete. *Good*: all remaining major bridges that do not meet the criteria for poor or fair.
Ontario Structure Inspection Manual [7]	Ontario Ministry of Transportation	Excellent–Poor	*Excellent*: in as constructed condition *Good*: first sign of minor defects is visible *Fair*: medium defects are visible *Poor*: severe defects are visible

measurement units of 3–5 standardized condition grades, and suggested maintenance intervention for each condition grade. In 2010, the FHWA noticed specific issues associated with the implementation of this manual by the various departments of transportation, mainly related to inconsistencies in definition of condition grades and differences in the selected elements for inspection [25].

4. Proposed Method for Bridge Condition Rating

As discussed, bridge condition assessment is based on periodic visual inspection conducted by well-trained and experienced inspectors. However, the different practices adopted different condition assessment grades and specified different elements for inspection. The ER approach provides a suitable platform to develop a bridge condition assessment method due to its flexibility in incorporating any number of uncertain factors and ability to function with available limited data. Hence, the approach does not impose any limitations on the number of condition assessment grades or the number of bridge elements. In addition, the ER method is flexible to use different assessment grades for each element of the bridge if needed. The proposed method in this research utilizes paired comparison technique to enable the assessment of relative weights between the different bridge elements. The utilization of the paired comparison technique along with the ER method enables the application of the proposed method to any of the existing bridge condition assessment practices or standards. The expert is required to specify the bridge elements, and then, the method can assess the relative weights through an intuitive pairwise comparison procedure. The proposed method introduces a new approach to assess the BPA quantitatively through the implementation of MCS. The final step in the proposed method is using the analytic ER algorithm to combine the basic probability assignments into an overall belief function reflecting the condition rating of the whole bridge structure. The sequence of the various steps of the proposed method is shown in Figure 1.

TABLE 2: Bridge elements and weights used in New York BMS.

Elements	Weights	Normalized weights
1. Bearing	6	0.083
2. Backwalls	5	0.069
3. Abutments	8	0.111
4. Wingwalls	5	0.069
5. Bridge seats	6	0.083
6. Primary members	10	0.139
7. Secondary members	5	0.069
8. Curbs	1	0.014
9. Sidewalks	2	0.028
10. Deck	8	0.111
11. Wearing surface	4	0.056
12. Piers	8	0.111
13. Joints	4	0.56

The following subsections explain the main steps of the proposed method.

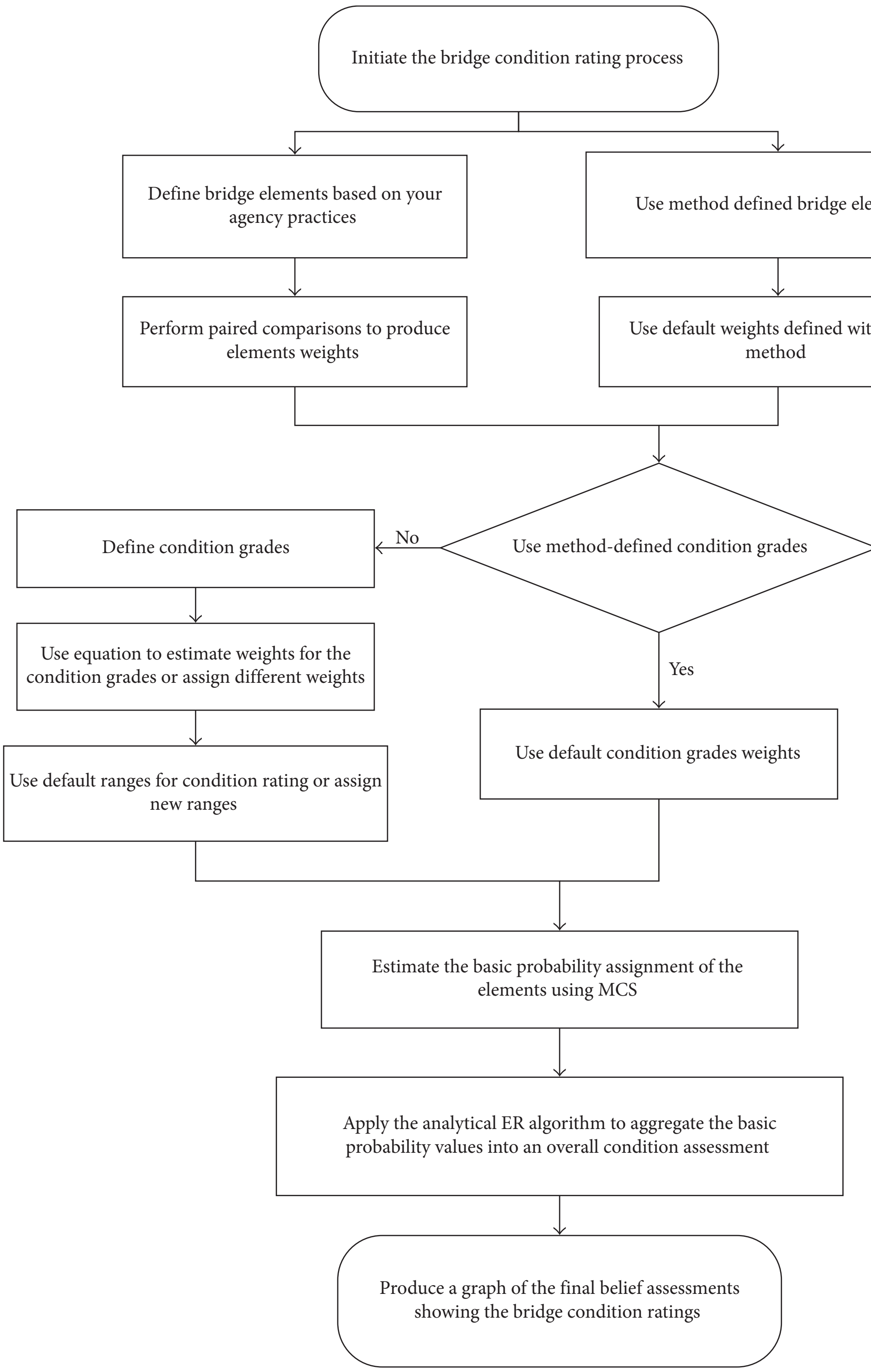


Figure 1: Flowchart for the condition assessment and rating method of concrete bridges.

4.1. Identifying Bridge Elements and Assigning Their Weights. Typically, any bridge consists of three major components: deck, superstructure, and substructure. In addition to these major components, several other elements are recognized. For instance, New York BMS breaks down the bridge into 13 elements as shown in Table 2. Examining the several bridge elements can be costly and is not always feasible due to limited resources and accessibility issues. The proposed method focuses on the three major components: deck, superstructure, and substructure. These are the default components included in the proposed method, as described in Figure 1. The components are divided into default elements for inspection and condition assessment purposes. At the same time, the method provides flexibility to revise the set of

Table 3: Paired comparisons for the bridge deck subelements provided by a bridge engineer.

A: wearing surface					
A	B: sidewalk				
C	C	C: deck topside			
D	D	C	D: deck underside		
A	B/E	C	D	E: curbs	
A/F	F	C	D	F	F: expansion joints

the default elements, so bridge engineer can identify specific important elements to be included in the assessment process.

Within the proposed method, the bridge engineer can either choose to use the standard weights assigned to the various elements used by their agency, such as the weights adopted by New York BMS (Table 2) or to produce the elements weights based on experience. In the latter case, paired comparisons can be used to extract the expert judgments and to evaluate the elements weight. The proposed approach is designed to be simple, intuitive, and flexible. To explain the approach, the bridge deck is used. The deck consists of six elements, namely: (1) the wearing surface, (2) the sidewalk, (3) the topside, (4) the underside, (5) the curbs, and (6) the expansion joints. The bridge engineer needs to fill each block in the matrix, such as the one provided in Table 3, to compare the two corresponding elements in pairs and to select the more important one. For instance, when the deck topside is compared to the wearing surface, the topside is more important, and the letter C is provided in the corresponding block in the matrix to reflect this judgment. If both elements have equal importance, then both elements are selected, such as the case in Table 3, where the bridge engineer assessed the expansion joints and the curbs to have the same level of importance.

The provided judgments can be translated into weights for the various elements depending on the frequency of selection of each element. The weight for each element is the frequency of the element selection divided by the total number of paired comparisons (15 in this case). For example, the wearing surface was selected 2.5 times (half time as one of the selections was shared with the expansion joints) so the weight is 2.5/15 yielding a weight of 0.17. Table 4 shows weights of the deck elements.

Table 4: Weights of the bridge deck subelements.

Bridge element	Number of selections	Weight
A	2.5	0.17
B	0.5	0.03
C	5.0	0.33
D	4.0	0.27
E	0.5	0.03
F	2.5	0.17

4.2. Selecting Assessment Grades and Assigning the Weights. As discussed, a variety of assessment grade and standards have been used in practice to rate the condition of bridge elements, including numeric rating scales such as 0 to 5 or 1 to 9 and linguistic expressions such as excellent, good, and poor. Our review of inspection practices (summarized in Table 1) shows that several manuals and condition rating methods adopted four or five main condition states and allowed for intermediate condition states to be defined as transition between the main states. Roberts and Shepard [29] developed a new index and proposed it as an improved numerical rating system that can assist in maintenance and repair decision-making. The index computations allow for selecting three, four, or five condition grades (State 1 to State 3, State 1 to State 4, or State 1 to State 5). They provided a formulation to assess the weights associated with any number of condition grades as in the following equation:

$$\mathrm{WF} = \left[1 - (\text{condition state\#} - 1)\left(\frac{1}{\text{state count}} - 1\right)\right]. \tag{1}$$

For example, if the bridge inspector uses five condition states ranging from State 1 (brand new condition) to State 5 (worst condition), the weights are 1, 0.75, 0.5, 0.25, and 0 for condition States 1, 2, 3, 4, and 5, respectively. Ontario BMS adopted similar approach to the one developed by Roberts and Shepard, but the number of condition states was fixed to four (excellent, good, fair, and poor) and gave flexibility to the decision maker to assign the weights to these grades [30]. The proposed method here implements a default set of condition states and allows for using alternative condition states if necessary. The default condition states are excellent, good, fair, and poor, and the weights assigned to these four condition states are 0.9, 0.7, 0.45, and 0.15, respectively. These condition states and weights were recommended by bridge engineers during interview conducted to solicit their agency bridge management practices. At the same time, the proposed method provides flexibility to select different grades and weights.

4.3. ER Framework and Analytical Assessments Integration. The ER theory uses belief structure as an effective approach for modelling uncertainties since the structure has probabilistic nature and has the ability to function even in case of missing data or ignorance [31, 32]. While implementing the ER theory, it is assumed that a frame of discernment (θ) is identified to include all the hypotheses under consideration where these hypotheses are exhaustive and mutually exclusive. Also, in this theory, it is assumed that with more evidence available, the hypothesis gets closer to the more precise possibility. The main concept in the ER theory is the BPA. The BPA is formally defined as the degree of belief in a subset of θ mapped over the interval $[0, 1]$. The BPA is denoted by m, where $m(A)$ is the proportion of the total belief assigned to the subset A of θ. The BPA satisfies the following equations:

$$\begin{aligned} &m(A) \rightarrow [0,1], \\ &m(\emptyset) = 0, \\ &\sum_{A\subseteq\theta} m(A) = 1. \end{aligned} \tag{2}$$

Another important concept in the ER theory is the traditional D–S rule of combination. This rule aggregates two basic probability assignments $m_1(B)$ and $m_2(C)$ into a joint probability $m_{1\text{-}2}(A)$ estimated as follows:

$$m_{1\text{-}2}(A) = \frac{\sum_{B\cap C=A} m_1(B)m_2(C)}{\sum_{B\cap C\neq\emptyset} m_1(B)m_2(C)}, \tag{3}$$

where $A \neq \emptyset$ and $m_{1\text{-}2}(\emptyset) = 0$.

To support the multiple attribute decision analysis requirements, the ER traditional rule of combination was further extended and two algorithms were developed, namely, the analytical and the recursive ER algorithms [33, 34]. It is discussed in the literature that the analytical ER algorithm provides flexibility in aggregating a large number of attributes. In addition, its nonlinear features have been proven [22]. The analytical algorithm is implemented in this research.

The ER technique uses a distributed modelling framework to represent various quantitative and qualitative characteristics. Each characteristic is to be recognized with a set of assessment grades and a degree of uncertainty represented by a degree of belief. The distributed assessment model can evaluate element's condition with more than one grade, but the total degree of belief needs to sum up to 1. For assessment integration purpose, the ER combination rule is utilized to aggregate the attributes of the various elements contributing to the overall condition assessment of the bridge structure [33]. Utilization of the ER approach for condition assessment starts with identification of the various elements that are part of the bridge and their weights that reflect their importance in the overall condition rating. Then, the basic probability masses (BPAs) of the various assessment grades for each element must be determined. After that, the analytical ER algorithm can be used for assessment aggregation of the different factors or elements. The frame of discernment considered in this study contains N assessment grades as follows:

$$H = \{H_{\text{Poor}}, \ldots, H_n\}, \tag{4}$$

where H_{Poor} is the worst condition grade and H_n corresponds to the best condition state.

First step in the analytical ER is to convert the degrees of belief associated with the various assessment grades for each element to basic probability masses. The probability masses are calculated based on the relative weight of the element and the degree of belief in each assessment grade. It is assumed that the bridge structure includes I elements. Equations (5)–(15) below show analysis of the basic probability masses [35]:

$$m_{n,i} = m_i(H_n) = w_i\beta_{n,i}(a_l), \quad n = 1, \ldots, N, \ i = 1, \ldots, I, \tag{5}$$

where $m_{n,i}$ is the basic probability mass of the bridge element, w_i is the bridge element weight, and $\beta_{n,i}$ is the belief degree of the bridge element.

$$m_{H,i} = m_i(H) = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - w_i \sum_{n=1}^{N} \beta_{n,i}(a_l), \quad i = 1, \ldots, I \tag{6}$$

where $m_{H,i}$ is the probability mass assigned to the whole set H and is divided into two parts, $\overline{m}_{H,i}$ and $\tilde{m}_{H,i}$.

$$\overline{m}_{H,i} = \overline{m}_i(H) = 1 - w_i, \quad i = 1, \ldots, I, \tag{7}$$

$$\tilde{m}_{H,i} = \tilde{m}_i(H) = w_i\left(1 - \sum_{n=1}^{N} \beta_{n,i}(a_l)\right), \quad i = 1, \ldots, I, \tag{8}$$

$$m_{H,i} = \overline{m}_{H,i} + \tilde{m}_{H,i} \text{ and } \sum_{i=1}^{I} w_i = 1, \tag{9}$$

where $\overline{m}_{H,i}$ is produced by the relative importance of the bridge's elements and $\tilde{m}_{H,i}$ is due to the incompleteness in bridge assessment.

The analytical ER equations can be used then used for aggregating the assessments obtained from the various elements of the bridge structure. Equations (10)–(15) shown below are used for computing the aggregated overall assessments [29]:

$$\{H_n\} : m_n = k\left[\prod_{i=1}^{I}\left(m_{n,i} + \overline{m}_{H,i} + \tilde{m}_{H,i}\right) - \prod_{i=1}^{I}\left(\overline{m}_{H,i} + \tilde{m}_{H,i}\right)\right], \quad n = 1, \ldots, N \tag{10}$$

where k is the normalization factor of the analytical ER algorithm.

$$\{H\} : \tilde{m}_H = k\left[\prod_{i=1}^{I}\left(\overline{m}_{H,i} + \tilde{m}_{H,i}\right) - \prod_{i=1}^{I} \overline{m}_{H,i}\right], \tag{11}$$

$$\{H\} : \overline{m}_H = k\left[\prod_{i=1}^{I} \overline{m}_{H,i}\right], \tag{12}$$

$$k = \left[\sum_{n=1}^{N}\prod_{i=1}^{I}\left(m_{n,i} + \overline{m}_{H,i} + \tilde{m}_{H,i}\right) - (N-1)\prod_{i=1}^{I}\left(\overline{m}_{H,i} + \tilde{m}_{H,i}\right)\right]^{-1}, \tag{13}$$

$$\{H_n\} : \beta_n = \frac{m_n}{1 - \overline{m}_H}, \quad n = 1, \ldots, N, \tag{14}$$

$$\{H\}:\beta_H = \frac{\widetilde{m}_H}{1-\overline{m}_H}, \tag{15}$$

where β_n and β_H stand for the overall belief degrees of the aggregated assessments assigned to the assessment grades H_n and H, respectively.

Equations (14) and (15) above are used for normalization purpose of the combined probability assignments into overall belief degrees.

4.4. Quantifying the Basic Probability Assignment Using Monte Carlo Simulation. The BPA is a fundamental concept of the ER theory. It reflects the degree of belief in a subset of the frame of discernment. In case of bridge condition assessment, the frame of discernment contains all the possible condition states that an inspector can rate the bridge elements with. The total belief is proportionally mapped to the different elements by assigning a BPA to each bridge element reflecting the element condition rating. Then, the ER rule of combination (the core of the ER theory) is applied to combine the different BPA values. As discussed, the BPA is typically assigned by an expert. The expert assessments are subjective and can suffer from inconsistencies inherent in implementing human judgments and experience. Two different experts may review the same inspection report and assign two different probabilities to the reported condition rating of an element. Alternatively, the proposed method uses the MCS technique to quantitatively assess the BPA value based on the data reported in inspection reports.

The MCS is a stochastic technique to quantify uncertainties in a system or a model. The technique generates several possible scenarios by running any computational algorithm for hundreds or thousands of iterations to produce several possible outcomes. In each iteration, the simulation follows a standard procedure to generate random values of the uncertain variables. Then, all the generated possible outcomes are produced as a probability distribution with statistical analysis of the results. From the probability distribution, the probability of having the outcomes within any possible range of results can be identified.

A condition index model is needed to run the MCS and to evaluate probabilities of the different condition grades. The concept of health index (HI) implemented by Department of Transportation in California [29] is adopted for this purpose. The HI is based on assessing the remaining asset value of a bridge or network of bridges using bridge inspection results. Its rationale is that the asset value of a bridge element drops as the element deteriorates with time to lower condition states. On the contrary, the element asset value increases when maintenance or rehabilitation actions are performed to enhance the element condition rating. Building on this concept, a bridge element HI can be estimated as a weighted average of the different quantities of the elements and their condition states as follows:

$$\mathrm{HI} = \frac{\sum_i^n Q_i W_i}{Q_{\text{total}} W_{\text{new}}} \times 100, \tag{16}$$

Table 5: Paired comparison of elements structural importance.

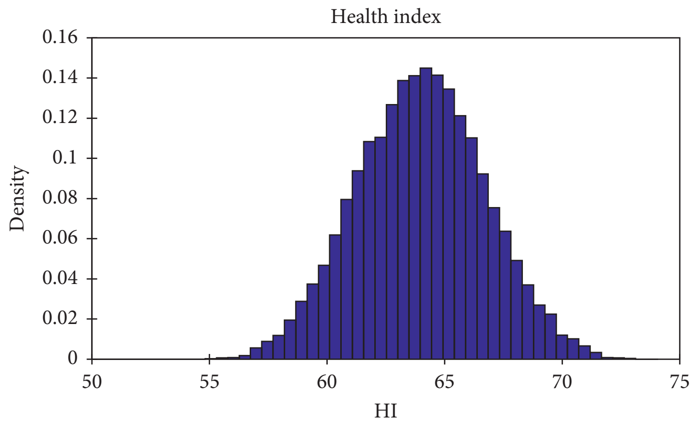
Component		Element	Weights
Deck (0.33)		Wearing surface	0.17
		Sidewalk	0.03
		Deck topside	0.33
		Deck underside	0.27
		Curbs	0.03
		Expansion joints	0.17
Superstructure (0.33)		Strings	0.30
		Floor beams	0.30
		Floor system bracing	0.05
		Girders	0.30
		Bearing devices	0.05
Substructure (0.33)	Abutments (0.50)	Bearing seats	0.04
		Backwall	0.33
		Wingwalls	0.33
		Piles	0.15
		Footing	0.15
	Piers (0.50)	Piles	0.42
		Footing	0.42
		Columns	0.08
		Caps	0.08

where Q_i is the quantity of the element inspected and assessed to be in the condition state i, W_i is the weight assigned to the condition state i, Q_{total} is the total quantity of the bridge element, and W_{new} is the weight assigned to the element when it was in a relatively new condition. As an example, the inspection report indicated that $100\,\text{m}^2$ of the girders surface area is rated as good and $80\,\text{m}^2$ is rated as fair, and then using the default weights, the HI is calculated as follows:

$$\mathrm{HI} = \frac{(0\times 0.9 + 100\times 0.7 + 80\times 0.45 + 0\times 0.15)}{(0.9\times 180)} \times 100 = 65. \tag{17}$$

The estimated HI can be assigned to a condition state by specifying a range of HI for each condition state. The proposed ranges for the different condition states are assigned to be consistent with the weight of each condition grade. For example, if the HI is above 85, then the element is in excellent condition; if less than 45, then the element is in poor condition; while 65 to 85 is good; and 45 to 65 is fair. In the above example, the bridge beams are exactly at the border point between good and fair condition states, and it is not clear how to rate them. Hence a more sensitive approach to quantify risk is needed.

The MCS can be implemented on this model to estimate the BPA values by building several scenarios for the HI while varying the weights assigned to the different condition ratings. The simulation technique accounts for uncertainty in defining the weights and provides stochastic analysis for the HI. The frequency of having the condition index in each condition state range estimates the probability of having the element in that condition state. The MCS approach can quantitatively estimate the basic probabilities of the different condition ratings to be assigned to each element, which assists in eliminating the subjectivity associated with the



Statistic	HI
Number of observations	10000
Minimum	55.255
Maximum	73.079
Range	17.824
Median	64.011
Mean	64.000
Variance (n)	7.381
Standard deviation (n)	2.717
Variation coefficient	0.042
Skewness (Pearson)	0.009
Kurtosis (Pearson)	−0.230
Geometric mean	63.942
Geometric deviation	1.043

Figure 2: The MCS results for the bridge deck.

Table 6: Bridge elements distributed assessments.

Component		Element	Distributed assessment (BPA)
Deck		Wearing surface	{(Poor, 0), (Fair, 0.30), (Good, 0.70), (Excellent, 0)}
		Sidewalk	{(Poor, 0), (Fair, 0.20), (Good, 0.80), (Excellent, 0)}
		Deck topside	{(Poor, 0), (Fair, 0.25), (Good, 0.75), (Excellent, 0)}
		Deck underside	{(Poor, 0), (Fair, 0.40), (Good, 0.60), (Excellent, 0)}
		Curbs	{(Poor, 0), (Fair, 0.10), (Good, 0.90), (Excellent, 0)}
		Expansion joints	{(Poor, 0), (Fair, 0.15), (Good, 0.85), (Excellent, 0)}
Superstructure		Strings	{(Poor, 0.70), (Fair, 0.30), (Good, 0), (Excellent, 0)}
		Floor beams	{(Poor, 0.90), (Fair, 0.10), (Good, 0), (Excellent, 0)}
		Floor system bracing	{(Poor, 0.40), (Fair, 0.60), (Good, 0), (Excellent, 0)}
		Girders	{(Poor, 0.80), (Fair, 0.20), (Good, 0), (Excellent, 0)}
		Bearing devices	{(Poor, 0.40), (Fair, 0.60), (Good, 0), (Excellent, 0)}
Substructure	Abutments	Bearing seats	{(Poor, 0.20), (Fair, 0.50), (Good, 0.30), (Excellent, 0)}
		Backwall	{(Poor, 0.30), (Fair, 0.40), (Good, 0.30), (Excellent, 0)}
		Wingwalls	{(Poor, 0.50), (Fair, 0.30), (Good, 0.20), (Excellent, 0)}
		Piles	{(Poor, 0), (Fair, 0.80), (Good, 0.20), (Excellent, 0)}
		Footing	{(Poor, 0.10), (Fair, 0.70), (Good, 0.20), (Excellent, 0)}
	Piers	**Piles**	**{(Poor, 0), (Fair, 0.60), (Good, 0.40), (Excellent, 0)}**
		Footing	{(Poor, 0), (Fair, 0.80), (Good, 0.20), (Excellent, 0)}
		Columns	{(Poor, 0.60), (Fair, 0.40), (Good, 0), (Excellent, 0)}
		Caps	{(Poor, 0), (Fair, 0.80), (Good, 0.20), (Excellent, 0)}

direct assignment through expert judgment. These basic probabilities can then be input into the ER algorithms to combine them and generate the overall bridge condition rating.

5. Case Study

The proposed method in this research is demonstrated with a case study. The data for the case study is extracted from bridge inspection report. The condition ratings used by the inspector are the four standard condition grades utilized in the proposed method which are poor, fair, good, and excellent conditions. A bridge engineer was requested to analyse the inspection report and to submit the needed paired comparisons to assess the elements weight. The technique is illustrated in the proposed method section, and the weights of the various elements of the bridge are shown below in Table 5.

To assess the probabilities associated with the different condition grades, the MCS is performed. The XL Stat software is used to run 10,000 iterations for each bridge element. The simulation assigns random values for the different condition grades to represent the weights associated with the corresponding condition grades. Then, the HI is estimated as per (16). This process is repeated 10,000 times, and the final statistics are produced by the software in form of tables and graphs. Figure 2 shows the MCS results for the bridge deck. The frequency of having the HI in each condition grade compared to the total number of iterations reflects the chance of having the element in the corresponding condition rating. For instance, for the bridge deck, around 2,500 iterations produced an HI in the range of fair and 7,500 iterations produced HI in the range of a good condition state. As a result, the bridge deck topside had

Table 7: Basic probability masses of the piers elements considering the various assessment grades.

Substructure component	Grade/basic probability mass $m_{n,i}$ Poor	Fair	Good	Excellent	$m_{H,i}$	$\overline{m}_{H,I}$	$\tilde{m}_{H,I}$
Piles	0	0.252	0.168	0	0.580	0.580	0
Footing	0	0.336	0.084	0	0.580	0.580	0
Columns	0.048	0.032	0.000	0	0.920	0.920	0
Caps	01	0.064	0.016	0	0.920	0.920	0

a 25% chance of receiving fair rating and 75% chance of receiving good rating.

The MCS is performed for all the bridge elements, and the basic probabilities produced are shown in Table 6.

Since the BPA values and elements weights are determined, the ER analysis can be performed. The ER analytical algorithm can be applied for assessment aggregation and overall beliefs calculation. The details of the calculations are illustrated with a sample numerical example for the assessment of the bridge substructure. The steps below show the calculation process for the degrees of belief, which illustrate the main steps needed to estimate the overall condition of the bridge. Substructure component with its abutments and piers elements is considered for calculation demonstration as shown below. The Piles element from the piers substructure component is considered first with the following distributed assessment and weight:

(i) Distributed assessment: {(Poor, 0), (Fair, 0.60), (Good, 0.40), (Excellent, 0)}

(ii) Weight: 0.42

Step 1. Calculate the basic probability masses of the bridge element in the various assessment grades:

(i) $m_{\text{Fair,Piles}} = m_{\text{Piles}}(H_{\text{Fair}}) = w_{\text{Piles}} \times \beta_{\text{Fair,Piles}} = 0.42(0.60) = 0.252$

(ii) $m_{\text{Good,Piles}} = m_{\text{Piles}}(H_{\text{Good}}) = w_{\text{Piles}} \times \beta_{\text{Good, Piles}} = 0.42(0.40) = 0.168$

Step 2. Calculate the probability mass assigned to the whole set H:

(i) $m_{H,\text{ Piles}} = m_{\text{Piles}}(H) = 1 - \sum_{n=1}^{4} m_{n,\text{ Piles}} = 1 - w_{\text{Piles}} \sum_{n=1}^{4} \beta_{n,\text{ Piles}} = 1 - (0 + 0.252 + 0.168 + 0) = 0.580$

(ii) $\overline{m}_{H,\text{ Piles}} = \overline{m}_{\text{Piles}}(H) = 1 - w_{\text{Piles}} = 1 - 0.42 = 0.580$

(iii) $\tilde{m}_{H,\text{ Piles}} = \tilde{m}_{\text{Piles}}(H) = w_{\text{Piles}}(1 - \sum_{n=1}^{4} \beta_{n,\text{Piles}}) = 0.42(1 - (0 + 0.60 + 0.40 + 0)) = 0$

(iv) $m_{H,\text{Piles}} = \overline{m}_{H,\text{Piles}} + \tilde{m}_{H,\text{Piles}} = 0.580 + 0 = 0.580$

Steps 1 and 2 are repeated for the other elements in the piers of the substructure bridge component. The data in Table 7 show the grade probability distribution of the various elements.

Step 3. Aggregate the basic probability masses from the various elements for each assessment grade:

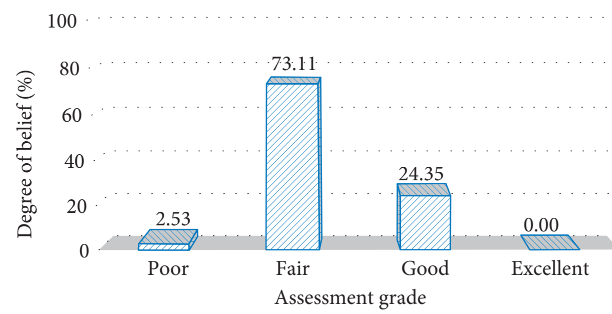


Figure 3: Overall condition assessment of the piers element of the substructure bridge component.

(i) $k = \left[\sum_{n=1}^{4}\prod_{i=1}^{4}(m_{n,i} + \overline{m}_{H,i} + \tilde{m}_{H,i}) - (N-1)\prod_{i=1}^{4}(\overline{m}_{H,i} + \tilde{m}_{H,i})\right]^{-1} = ((1.726) - (4-1)(0.285))^{-1} = 1.148$

(ii) $\{H_n\} : m_{\text{Poor}} = k\left[\prod_{i=1}^{4}(m_{n,i} + \overline{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{4}(\overline{m}_{H,i} + \tilde{m}_{H,i})\right] = 1.148(0.300 - 0.285) = 0.017$

(iii) $\{H_n\} : m_{\text{Fair}} = k\left[\prod_{i=1}^{4}(m_{n,i} + \overline{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{4}(\overline{m}_{H,i} + \tilde{m}_{H,i})\right] = 1.148(0.714 - 0.285) = 0.492$

(iv) $\{H_n\} : m_{\text{Good}} = k\left[\prod_{i=1}^{4}(m_{n,i} + \overline{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{4}(\overline{m}_{H,i} + \tilde{m}_{H,i})\right] = 1.148(0.428 - 0.285) = 0.164$

(v) $\{H_n\} : m_{\text{Excellent}} = k\left[\prod_{i=1}^{4}(m_{n,i} + \overline{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{4}(\overline{m}_{H,i} + \tilde{m}_{H,i})\right] = 1.148(0.285 - 0.285) = 0$

(vi) $\{H\} : \tilde{m}_H = k\left[\prod_{i=1}^{4}(\overline{m}_{H,i} + \tilde{m}_{H,i}) - \prod_{i=1}^{4}\overline{m}_{H,i}\right] = 1.148(0.285 - 0.285) = 0$

(vii) $\{H\} : \overline{m}_H = k[\prod_{i=1}^{4}\overline{m}_{H,i}] = 1.148(0.285) = 0.327$

Step 4. Normalize the combined probability assignments into overall belief degrees:

(i) $\{H_n\} : \beta_{\text{Poor}} = m_{\text{Poor}}/1 - \overline{m}_H = 0.017/1 - 0.327 = 0.025$

(ii) $\{H_n\} : \beta_{\text{Fair}} = m_{\text{Fair}}/1 - \overline{m}_H = 0.492/1 - 0.327 = 0.731$

Table 8: Basic probability masses of the abutments elements considering the various assessment grades.

Substructure component	Grade/basic probability mass $m_{n,i}$ Poor	Fair	Good	Excellent	$m_{H,i}$	$\overline{m}_{H,I}$	$\tilde{m}_{H,I}$
Bearing seats	0.008	0.020	0.012	0	0.960	0.960	0
Backwall	0.099	0.132	0.099	0	0.670	0.670	0
Wingwalls	0.165	0.099	0.066	0	0.670	0.670	0
Piles	0	0.120	0.030	0	0.850	0.850	0
Footing	0.015	0.105	0.030	0	0.850	0.850	0

(iii) $\{H_n\} : \beta_{\text{Good}} = m_{\text{Good}}/1 - \overline{m}_H = 0.164/1 - 0.327 = 0.244$

(iv) $\{H_n\} : \beta_{\text{Excellent}} = m_{\text{Excellent}}/1 - \overline{m}_H = 0/1 - 0.327 = 0$

(v) $\{H\} : \beta_H = \tilde{m}_H/1 - \overline{m}_H = 0/1 - 0.327 = 0$

The data in Figure 3 show the overall condition assessment of the piers element of the bridge. However, for overall condition assessment of the substructure component, Steps 1 to 4 need to be repeated for the abutments elements.

Table 8 shows the basic probability masses of the abutments elements. After performing Steps 3 and 4, the normalized overall belief degrees of the abutments element are found to be the following: {(Poor, 0.29), (Fair, 0.49), (Good, 0.23), (Excellent, 0)}.

The overall condition assessments of the piers and abutments are combined for overall substructure condition assessment (Figure 4). The same steps are preformed on the bridge deck and bridge superstructure to find their overall conditions. Then, the condition assessment of the bridge deck, superstructure, and substructure are aggregated to assess the overall condition of the inspected bridge. Overall, the bridge was assessed to be in poor, fair, and good conditions with 26.93%, 42.66%, and 30.41% probability, respectively, as shown in Figure 5.

The obtained combined distributed assessment is a definite enhancement over evaluating the bridge elements individually or evaluating the overall condition with a single numerical index. The bridge deck, a major element of the bridge structure, and its elements in this case are in good conditions, which individually may give a misleading assessment of the bridge overall condition and the urgency of maintenance needs. However, the elements of the bridge superstructure are mostly in poor condition, impacting the overall condition of the bridge, which clearly indicates that the bridge requires maintenance intervention.

6. Summary and Conclusions

Based on reviewing bridge inspection manuals and practices, it is clearly noticed that inspection standards and guidelines vary from one country to another and may even vary in the different states or districts within the same country, despite the fact most of the practices rely mostly on the same approach of visual inspection for data collection. In addition, it is widely reported in the literature that results obtained from bridge visual inspection are inevitably uncertain and subjective. The current research contributes a flexible condition rating method that can function with different bridge inspection standards and guidelines and account for uncertainties inherent in the visual inspection process. Generally, uncertainties in the bridge condition assessment are addressed using either fuzzy logic or probabilistic analysis. The fuzzy logic quantifies subjectivity associated with using language expressions for condition ratings while probabilistic analysis focuses on randomness and uncertainties associated with quantifying the condition rating. The bridge deterioration process is stochastic in nature, and probabilistic analysis can better depict stochastic behaviour. The proposed method uses the analytical ER approach that treats condition assessments as probabilistic assessment grades. The method integrates the MCS technique with the ER approach to enhance bridge condition rating by eliminating subjectivity in assessing the initial degrees of belief. The MCS method quantitatively estimates the BPA values that are aggregated by means of the recursive ER algorithm to

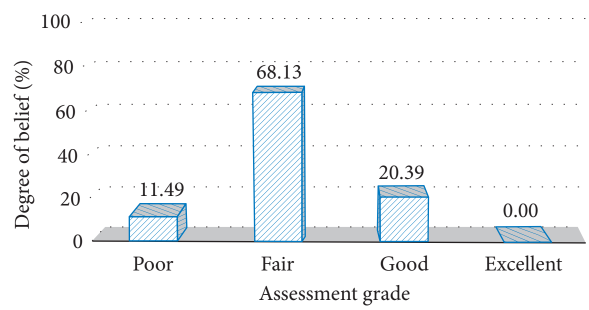


Figure 4: Overall condition assessment of the substructure bridge component.

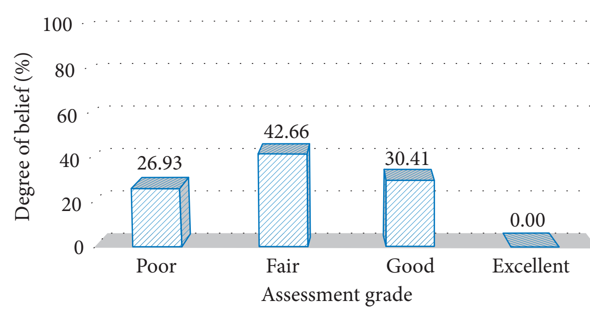


Figure 5: Overall bridge condition assessment based on the analytical ER algorithm.

produce a robust overall condition rating of the bridge structure.

The proposed method can enhance bridge condition assessment and rating processes because of the following reasons: (1) flexibility in aggregating any number of basic probabilities assigned to any number of bridge elements and condition grades; (2) flexibility in defining the bridge elements and assigning the weights. The weights can be used as the default weights defined within the proposed method or assessed by the decision maker through the intuitive paired comparison technique; (3) the approach allows for incorporating new evidence as new inspection records become available; and (4) both the MCS and the ER are probabilistic techniques that are suitable and consistent in modelling uncertainties associated with the bridge condition assessment process.

The proposed method requires the expert input in certain cases, especially if the expert decided to use different parameters other than the ones embedded within the framework, such as when the expert decides to revise the weights of the bridge elements or condition grades. In this case, subjective assessments are needed. The intuitive paired comparison technique is implemented to assist the expert in estimating the different elements weights in a systematic way. Further work to study the uncertainty in the assigned weights to the different elements can enhance the proposed method. Other future research directions can include (1) to study the implementation of the recursive ER algorithm in bridge condition assessment and to compare its results with the results obtained from the analytical ER algorithm, (2) to compare the probabilistic ER analysis with the fuzzy-based methods, and (3) to apply the proposed method on more case studies and other civil engineering applications.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Identifying Political Risk Management Strategies in International Construction Projects

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International construction projects are plagued with political risk, and international construction enterprises (ICEs) must manage this risk to survive. However, little attention has been devoted to political risk management strategies in international construction projects. To fill this research gap, a total of 27 possible strategies were identified through a comprehensive literature review and validated by a pilot survey with 10 international experts. Appraisals of these 27 strategies by relevant professionals were collected using questionnaires, 155 of which were returned. Exploratory factor analysis was conducted to explore the interrelationships among these 27 strategies. The results show that all of the 27 strategies are important for political risk management in international construction projects. Moreover, these 27 strategies were clustered into six components, namely, (1) making correct decisions, (2) conducting favorable negotiations, (3) completing full preparations, (4) shaping a good environment, (5) reducing unnecessary mistakes, and (6) obtaining a reasonable response. The 6 components can be regarded as 6 typical management techniques that contribute to political risk management in the preproject phase, project implementation phase, and postevent phases. The findings may help practitioners gain an in-depth understanding of political risk management strategies in international construction projects and provide a useful reference for ICEs to manage political risks when venturing outside their home countries.

1. Introduction

With the rapid development of economic globalization, the global construction market has thrived in the past decade [1]. Moreover, the large market for construction in Asia, Africa, and Latin America will create widespread prosperity and opportunities for international construction enterprises (ICEs). By taking advantage of these opportunities, increasing numbers of international contractors will expand into the international construction market [2].

However, opportunities are always accompanied by risks, and ICEs will be exposed to new risks when venturing outside their home countries [3, 4]. ICEs have witnessed a dramatic increase in political risks around the world, such as the credit crises in Greece, Venezuela, and Congo; the wars in southern Sudan, Syria, Afghanistan, and Libya; the terrorist attacks in Europe, the Middle East, Central Asia, and South Asia; and the coups in Niger, Thailand, and Honduras [2, 4, 5]. These risks had a very large negative impact on the global market and resulted in great losses for ICEs.

Given the increasingly complex business environment, political risks should not be ignored by ICEs when they approach global markets [2, 6, 7]. Political risk in international construction projects refers to uncertainty related to political events (e.g., political violence, regime changes, coups, revolutions, breaches of contract, terrorist attacks, and wars) and to arbitrary or discriminatory actions (e.g., expropriation, unfair compensation, foreign exchange restrictions, unlawful interference, capital restrictions, corruption, and labor restrictions) by host governments or political groups that may have negative impacts on ICEs [6]. Compared with the nonsystematic risks (e.g., technical risk, quality risk, procurement risk, and financial risk) of construction projects, political risk is more complex, unpredictable, and devastating and is usually outside the scope of normal project activities [2].

Much of the extant literature has focused on political risks in international general business [8, 9] but has paid less attention to political risks in international construction projects. In most cases, political risk management is practiced only as a part of risk management at the project level in construction projects. However, project-level political risks can also affect enterprises' objectives (e.g., financial, reputation, stability, survival, development, and strategic decisions) [10]. Implementation of political risk management only at the project level has some drawbacks: (1) lack of a comprehensive understanding of political risks; (2) overemphasis on short-term project goals and less consideration of corporate strategic objectives; (3) constraints because of limited resources or inappropriate resource allocation among projects; and (4) lack of accumulation and sharing of risk management experience. Therefore, risk management only at the project level no longer seems to be sufficient to help ICEs to address political risks in the global market [11].

Hence, political risk management in international construction projects should be conducted jointly at both the project and firm levels by considering the various types of risk and linking risk management strategies to the enterprise's objectives. Successful political risk management should be based on sufficient resources and information as important components of the decision-making process are continually improved and enhanced [12]. At the firm level, political risks can be treated as part of the entire risk portfolio of an enterprise and can be addressed across multiple business areas [13, 14]. Implementation of political risk management at the firm level can lead to better coordination and consolidation of the resources and goals of the enterprise, which is more conducive to the long-term stability and development of ICEs [15].

This study focuses on the political risk inherent in international construction projects and aims at identifying the strategies available for ICEs to manage political risk. The specific objectives of this study are to (1) identify possible risk management strategies that can address political risks in international construction projects, (2) evaluate the importance of the strategies, and (3) explore the interrelationships among those strategies and their practical applications in international construction projects.

Because less attention has been devoted to political risk management in international construction projects, this paper can enrich the understanding of risk management in the field of international construction. Furthermore, this study may help practitioners clearly understand political risk management strategies in international construction projects and provide guidance for ICEs regarding how to address political risk when venturing outside their home countries.

2. Literature Review

Political risk management has been a popular topic in the field of international business (e.g., foreign direct investment, trade in goods, and international joint ventures). Several strategies have been proposed to address political risks, such as investing only in safe environments, increasing the required return, adapting to particular business environment conditions, sharing risks with other firms [8], improving relative bargaining power [9], transferring risks to an insurance company [16], reducing vulnerabilities [17], spreading risk by investing in several countries, enhancing the core competitiveness [18], and implementing localization and involvement strategies [1, 19].

Previous studies regarding risk management in construction projects have covered a wide variety of areas, such as overall risk management [20], safety risk management [21], financial risk management [22], quality risk management [23], risk assessment [24], advanced technology-driven risk management [25], and risk management in public-private partnerships [26, 27]. However, less attention has been devoted to political risk management in international construction projects. In some studies, political risk was mentioned only as a subset of external risks [28, 29].

Several studies have been conducted to identify political risk events [2, 30] and political risk factors [5, 6, 31] in international construction projects. Although these studies can help international contractors gain a better understanding of political risks in international construction projects, they provide less guidance regarding how to manage political risk. It is obvious that knowledge and experiences associated with political risk management should be extended to the international construction business by considering overall political risk management strategies throughout the life of projects and the interrelation between the project and firm levels.

3. Methods

3.1. Strategy Identification and Survey. Based on an overview of the literature on political risk and risk management, a total of 27 possible risk management strategies were identified and were coded as S01 to S27 (Table 1).

A pilot survey was performed with 10 experts to verify the comprehensiveness of the preliminary strategies. These experts included (1) four professors (one each from Australia, Hong Kong, Singapore, and South Africa) engaged in research on business management and risk management, (2) two professors (one each from the United States and China) engaged in research on project management, and (3) four senior managers (one each from China Communications Construction Group Limited, Power Construction Corporation of China, China State Construction Engineering Corporation, and China Railway Group Limited). All the 10 experts had more than 20 years of work experience in their field. In their suggestion, no strategies were added or deleted; instead, descriptions of some strategies were added to ensure accuracy in understanding and to avoid ambiguity. For example, "S01, making a higher tender offer" refers to the premium for the retained political risks of an ICE.

The pilot survey was used to develop a structured questionnaire that comprised three sections: (1) a brief introduction of political risk and a description of some strategies; (2) questions to profile the company, work experience, title, and location of the respondents; and (3) questions to evaluate the

Table 1: Political risk management strategies.

Strategy	Reference								
	[8]	[3]	[32]	[5]	[52]	[33]	[2]	[8]	[34]
S01: making a higher tender offer	X	—	—	—	—	—	—	X	—
S02: conducting market research	X	X	—	X	X	—	X	X	—
S03: buying risk insurance	X	—	—	X	X	—	X	—	X
S04: adopting optimal contracts	—	—	X	—	—	X	—	—	X
S05: implementing a localization strategy	X	X	—	X	—	—	X	—	X
S06: avoiding misconduct	X	X	—	X	—	—	X	—	X
S07: adopting closed management of the construction site	X	—	—	X	X	—	X	X	—
S08: supporting environmental protection	X	—	—	—	—	—	—	—	—
S09: abiding by the traditional local culture	X	X	—	X	—	—	—	—	—
S10: making contingency plans	X	—	—	—	X	—	X	X	X
S11: obtaining the corresponding guarantee	—	—	—	X	—	X	X	—	X
S12: implementing an emergency plan	X	—	—	—	X	—	X	X	X
S13: forming joint ventures with local contractors	X	—	X	X	—	—	—	—	X
S14: conducting a postresponse assessment	X	—	—	—	X	—	X	—	—
S15: sending staff to training programs	X	—	—	—	—	—	—	—	X
S16: settling disputes through renegotiation	—	—	X	X	—	—	—	—	X
S17: choosing suitable projects	—	—	—	X	—	X	—	—	X
S18: building proper relations with host governments	—	X	X	X	—	—	X	—	—
S19: maintaining good relations with powerful groups	—	X	X	X	—	X	X	—	X
S20: creating links with local business	X	X	X	X	—	X	X	—	X
S21: changing the operation strategies	—	—	X	—	—	X	X	X	—
S22: controlling core and critical technology	—	X	—	—	—	X	—	X	X
S23: choosing a suitable entry mode	X	—	—	X	—	X	X	X	X
S24: employing capable local partners	X	X	X	X	—	X	—	—	X
S25: building up reputation	X	—	—	X	—	—	X	—	—
S26: allocating extra funds	—	—	X	—	X	—	X	—	—
S27: maintaining good relations with the public	—	X	X	—	—	X	X	—	X

importance of the 27 strategies using a five-point Likert scale where 5 = very high, 4 = high, 3 = medium, 2 = low, and 1 = very low.

Then, a list of selected experts was developed, and they included (1) 300 international academics who focus on related studies—their personal information was collected from their publications—and (2) 500 practitioners with extensive experience in international project management—drawn from 50 Chinese construction enterprises that were selected from the 2016 top 250 international contractors according to *Engineering News-Record* (ENR). The contact information of the 500 practitioners was collected from the Chinese construction management research sector, alumni associations, and the websites of their enterprises.

From March to May 2017, the questionnaire was disseminated to these experts and a total of 158 responses were returned, of which three were incomplete or inappropriately filled out. The valid 155 responses represent a response rate of 19%. As indicated in Table 2, among the 155 respondents, 56 were from academia and 99 were from industry. All the respondents had over 5 years' work experience, and 52% had over 10 years' work experience in industry or academia. Of the 56 academics, 28 were from China (including Hong Kong and Macao), and another 28 were from overseas. Among the 99 practitioners, 38, 26, 9, 5, 8, and 5 were from the divisions of Chinese construction enterprises in Asia (not including China), Africa, Europe, North America, South America, and Australia, respectively. Moreover, all practitioners had experienced political risk in the overseas construction market.

3.2. Exploratory Factor Analysis. The exploratory factor analysis has proven to be very useful for identifying the potential relationships between several sets of data and has frequently been employed in studies related to construction management [11, 31, 35]. The exploratory factor analysis is often used to create theories in a new research area, such as components, correlations, and relative weightings of a list of variables [36].

A sample with 5-point Likert scale data used in exploratory factor analysis should meet two conditions: (1) the size of the valid sample must be greater than 100 or five times the number of items [37] and (2) the data for the sample must satisfy the recommended alpha reliability test, Bartlett's test of sphericity, and the Kaiser–Meyer–Olkin (KMO) test of sampling adequacy [31].

In this study, the number of valid questionnaires is 155, Cronbach's alpha coefficient is 0.932 (>0.700, F statistic = 17.382, significance level = 0.000), the KMO index is 0.878 (≥0.500), and Bartlett's test of sphericity ($\chi^2 = 1497.243$, $df = 205$, significance level = 0.000) is significant ($p < 0.050$), indicating that these data are suitable for the exploratory factor analysis [38–40]. The factor analysis of the 27 political risk management strategies was performed using the principal component analysis and varimax

Table 2: Profile of the respondents.

Characteristic	Categorization	Academia (N = 56)		Practitioner (N = 99)		Overall (N = 155)	
		N	%	N	%	N	%
Work experience	Over 20 years	8	14	10	10	18	12
	16–20 years	15	27	12	12	27	17
	11–15 years	17	30	28	28	45	29
	5–10 years	16	29	49	49	65	42
Title	Professor	22	39	—	—	22	14
	Associate professor	19	34	—	—	19	12
	Assistant professor/lecturer	15	27	—	—	15	10
	Senior manager	—	—	29	29	29	19
	Department manager	—	—	28	28	28	18
	Project manager	—	—	42	42	42	27
Location	China	28	50	8	8	36	23
	Asia (excl. China)	14	25	38	38	52	34
	Africa	2	4	26	26	28	18
	Europe	5	9	9	9	14	9
	North America	4	7	5	5	9	6
	South America	0	0	8	8	8	5
	Australia	3	5	5	5	8	5

rotation methods implemented using SPSS 22.0 software. The number of components was determined by successively using latent root criteria (eigenvalues > 1.000) [41]. As suggested by Malhotra, the cumulative variance of the produced components should be greater than 60.000%. To increase the correlation between strategies and components, the qualified strategies in each component should have a factor loading ≥0.500 [42]. The internal consistency of the components should satisfy two conditions: Cronbach's alpha of each component ≥0.700 [38] and the item-to-total correlation of each retained measure ≥0.400 [43].

4. Results

4.1. Results of the Questionnaire Survey. Table 3 presents the evaluation results of the 27 political management strategies. The average values of the 27 strategies range from 3.27 (S21, changing the strategies) to 4.40 (S17, choosing suitable projects). All of them were significantly greater than 3 at the $p = 0.05$ level (two tailed) in the one-sample t-test, indicating that the 27 strategies had significant importance in managing political risk in international construction projects. The five most important strategies were (1) choosing suitable projects (S17, average value 4.40), (2) building proper relations with host governments (S18, average value 4.30), (3) conducting market research (S02, average value 4.29), (4) avoiding misconduct (S06, average value 4.26), and (5) choosing a suitable entry mode (S23, average value 4.22). The p values of the 27 strategies were greater than 0.05 in the independent-sample t-test. Therefore, there were no significant differences in the average values of the strategies between scholars and practitioners.

4.2. Results of Exploratory Factor Analysis. As illustrated in Table 4, a total of six components with eigenvalues greater than 1.000 were explored. The cumulative variance of the six components was 61.208%, thus exceeding 60.000%. The 27 strategies were divided into the six components according to their loading on each component of more than 0.500. Although the loading of strategy "S13 forming joint venture with local contractors" in the first component was 0.521, it was still removed from subsequent analyses due to the low value of its communality (0.399 < 0.500) and item-to-total correlations (0.301 < 0.400). After the adjustment, Cronbach's alpha coefficient of the first component and the communalities of the remaining six strategies in the first component increased. Cronbach's alpha coefficients of the six components ranged from 0.743 to 0.857, and the item-to-total correlations of the remaining 26 strategies ranged from 0.478 to 0.653; thus, the model is reliable.

4.3. Results of the Validity Test. The Pearson correlation analysis (2 tailed) was applied to check the validity of the results of the exploratory factor analysis. The strategies clustered into a component should be significantly correlated [44]. The results revealed that for each component all the strategies were correlated with the others, and thus, the strategies can explain political risk management in that dimension. Due to space limitations, only the correlations between strategies in the first component are presented in Table 5.

5. Discussion

5.1. Connotation of the Components. The connotation of each component is determined by the commonalities of the remaining measures it contains. On the basis of project management, risk management, and strategic management theories, the 6 components were renamed as follows: (1) making correct decisions (C1), (2) reducing unnecessary mistakes (C2), (3) completing full preparations (C3), (4) shaping a good environment (C4), (5) conducting favorable

Table 3: Ranking of the political risk management strategies.

Strategy	Academia		Industry		p value	Overall		
	Mean	Rank	Mean	Rank		Mean	Rank	p value
S01: making a higher tender offer	3.99	11	4.00	11	0.906	4.00	11	$<0.001^a$
S02: conducting market research	4.45	3	4.20	5	0.282	4.29	3	$<0.001^a$
S03: buying risk insurance	4.03	10	4.06	9	0.697	4.05	10	$<0.001^a$
S04: adopting optimal contracts	4.12	6	4.23	3	0.261	4.19	6	$<0.001^a$
S05: implementing a localization strategy	4.42	4	4.06	10	0.197	4.19	7	$<0.001^a$
S06: avoiding misconduct	4.45	2	4.15	6	0.089	4.26	4	$<0.001^a$
S07: adopting closed management of the construction site	3.41	22	3.85	12	0.537	3.69	18	$<0.001^a$
S08: supporting environmental protection	3.75	14	3.82	15	0.831	3.80	14	$<0.001^a$
S09: abiding by the traditional local culture	3.90	13	3.81	16	0.863	3.84	13	$<0.001^a$
S10: making contingency plans	4.10	9	4.09	8	0.606	4.09	9	$<0.001^a$
S11: obtaining the corresponding guarantee	3.98	12	4.22	4	0.401	4.14	8	$<0.001^a$
S12: implementing an emergency plan	3.18	26	3.55	23	0.244	3.42	24	$<0.001^a$
S13: forming joint ventures with local contractors	3.58	16	3.77	18	0.182	3.70	17	$<0.001^a$
S14: conducting a postresponse assessment	3.16	27	3.41	26	0.537	3.32	26	$<0.001^a$
S15: sending staff to training programs	3.43	20	3.62	21	0.628	3.55	21	$<0.001^a$
S16: settling disputes through renegotiation	3.28	25	3.43	25	0.617	3.38	25	$<0.001^a$
S17: choosing suitable projects	4.54	1	4.32	2	0.439	4.40	1	$<0.001^a$
S18: building proper relations with host governments	4.12	7	4.42	1	0.223	4.31	2	$<0.001^a$
S19: maintaining good relations with powerful groups	3.52	17	3.85	13	0.537	3.73	15	$<0.001^a$
S20: creating links with local business	3.43	21	3.70	19	0.377	3.60	20	$<0.001^a$
S21: changing the operation strategies	3.36	24	3.22	27	0.236	3.27	27	$<0.001^a$
S22: controlling core and critical technology	4.10	8	3.80	17	0.301	3.91	12	$<0.001^a$
S23: choosing a suitable entry mode	4.37	5	4.14	7	0.439	4.22	5	$<0.001^a$
S24: employing capable local partners	3.66	15	3.66	20	0.725	3.66	19	$<0.001^a$
S25: building up reputation	3.47	19	3.47	24	0.912	3.47	23	$<0.001^a$
S26: allocating extra funds	3.39	23	3.59	22	0.275	3.52	22	$<0.001^a$
S27: maintaining good relations with the public	3.49	18	3.83	14	0.137	3.71	16	$<0.001^a$

Note. [a]One-sample t-test result is significant (test value = 3) at the $p = 0.05$ significance level (two tailed).

negotiations (C5), and (6) obtaining a reasonable response (C6).

As shown in Figure 1, the six components may be divided into two dimensions of political risk management. Making correct decisions (C1), reducing unnecessary mistakes (C2), and obtaining a reasonable response (C6) are the components related to the reduction of risk exposure. When an ICE has a lower risk exposure, it has a lower risk level. In contrast, completing full preparations (C3), shaping a good environment (C4), and conducting favorable negotiations (C5) are the components associated with the promotion of risk response capability. A higher risk response capability indicates that an ICE has higher viability in an uncertain environment and is less likely to suffer damage arising from political risk. The components in the exposure reduction and capability promotion dimensions accounted for 38.975% and 29.233% of the total variance, respectively, thus indicating the leading role of reducing risk exposure and the supplementary role of improving risk response capability in political risk management in international projects.

In addition, the six components may be divided into groups with proactive, moderate, and passive characteristics. First, the components with a proactive characteristic (C1 and C4, which accounted for 26.040% of the total variance) are those utilized when making decisions or adapting to the local environment. Second, the components with a moderate characteristic (C2 and C3, which accounted for 24.742% of the total variance) are those applicable to a specific market or environment without specific risks. Third, the components with a passive characteristic (C6 and C5, which accounted for 19.420% of the total variance) are those related to specific risks. Compared to the passive strategies, the proactive and moderate strategies occupy more important positions in political risk management. In addition, ICEs are more likely to be resilient to political risks in the global market if they perform well with regard to the proactive strategies.

5.2. Application of the Components. As shown in Figure 2, the six components can be regarded as typical management techniques that contribute to political risk management in three different phases: the preproject phase, project implementation phase, and postevent phases. In the preproject phase, the premanagement techniques (C1, C5, and C3, which accounted for 39.975% of the total variance) can provide guidance for ICEs to avoid or transfer unacceptable risks and imply a higher offer for retained risks. In the project implementation phase, the interim management techniques (C4 and C2, which accounted for 24.404% of the total variance) can help ICEs adapt to the particular environmental conditions of the host country and reduce the probability and potential impacts of risks. In the postevent

Table 4: Results of the exploratory factor analysis.

Strategy	Communality	Item-to-total correlation	Component					
			1	2	3	4	5	6
S23	0.640	0.590	0.676	—	—	—	—	—
S05	0.530	0.490	0.653	—	—	—	—	—
S17	0.575	0.572	0.617	—	—	—	—	—
S22	0.632	0.585	0.598	—	—	—	—	—
S18	0.565	0.482	0.541	—	—	—	—	—
S02	0.652	0.511	0.509	—	—	—	—	—
S06	0.730	0.579	—	0.683	—	—	—	—
S07	0.648	0.497	—	0.667	—	—	—	—
S24	0.667	0.612	—	0.617	—	—	—	—
S08	0.543	0.515	—	0.595	—	—	—	—
S09	0.621	0.611	—	0.509	—	—	—	—
S15	0.742	0.592	—	—	0.739	—	—	—
S26	0.679	0.516	—	—	0.670	—	—	—
S03	0.512	0.527	—	—	0.525	—	—	—
S10	0.479	0.542	—	—	0.507	—	—	—
S27	0.532	0.621	—	—	—	0.682	—	—
S25	0.697	0.629	—	—	—	0.672	—	—
S20	0.632	0.637	—	—	—	0.586	—	—
S19	0.581	0.589	—	—	—	0.547	—	—
S04	0.561	0.478	—	—	—	—	0.663	—
S01	0.548	0.551	—	—	—	—	0.567	—
S11	0.629	0.557	—	—	—	—	0.550	—
S16	0.611	0.538	—	—	—	—	—	0.631
S12	0.710	0.539	—	—	—	—	—	0.618
S21	0.579	0.571	—	—	—	—	—	0.522
S14	0.576	0.653	—	—	—	—	—	0. 502
Cronbach's alpha			0.857	0.832	0.811	0.767	0.743	0.758
Eigenvalues			6.483	2.867	2.310	1.451	1.162	1.100
Variance (%)			15.233	13.587	11.155	10.817	9.265	8.150
Cumulative variance (%)			15.233	28.820	39.975	50.793	60.058	68.208

Note. Only loadings of 0.500 or above are shown. Extraction method: principal component analysis. Rotation method: varimax with Kaiser normalization. Rotation converged in 10 iterations.

phase, the postmanagement techniques (C6, 10.155% of the total variance) can help ICEs relieve the actual impacts of political risk and accumulate experience in political risk management.

Table 5: Pearson correlations for component one.

	S23	S05	S17	S22	S18	S02
S23	1.000	0.602^b	0.477^b	0.467^b	0.564^b	0.581^b
S05	—	1.000	0.388^a	0.491^b	0.413^b	0.432^b
S17	—	—	1.000	0.306^b	0.625^b	0.589^b
S22	—	—	—	1.000	0.427^a	0.371^b
S18	—	—	—	—	1.000	0.689^b
S02	—	—	—	—	—	1.000

[a]Correlation is significant at the $p = 0.05$ level (2 tailed). [b]Correlation is significant at the $p = 0.01$ level (2 tailed).

5.2.1. Making Correct Decisions (C1). This component explained the largest percentage of the total variance (15.233%) and contains six strategies: (1) conducting market research (S02), (2) choosing a suitable entry mode (S23), (3) choosing suitable projects (S17), (4) building proper relations with host governments (S18), (5) implementing a localization strategy (S05), and (6) controlling core and critical technology (S22). The average values of these six strategies (4.29, 4.21, 4.40, 4.31, 4.19, and 3.91, resp.) were relatively high, ranking 3rd, 5th, 1st, 2nd, 7th, and 12th, respectively, among the 27 strategies. All of them are strongly associated with decision-making activities, which can be observed as the most important part of political risk management.

Market research is a basic task for ICEs before they enter a country or contract a new project [3, 8]. Information about the target market can be obtained from the websites or reports of international organizations (e.g., The World Bank, International Monetary Fund, and World Trade Organization), nongovernmental organizations (e.g., industry associations, commercial banks, and insurance companies), and government agencies (e.g., ministries of construction, ministries of commerce, and foreign ministries) in the host and home countries. Based on a clear understanding of market conditions, ICEs can identify potential political events and their probabilities by using risk assessment. The results of market research and risk assessment can be used as evidence for decision making [45, 46]. In a high-risk country, ICEs should choose a flexible entry mode (e.g., sole-venture projects and joint-venture projects with short durations) to reduce their exposure to environmental

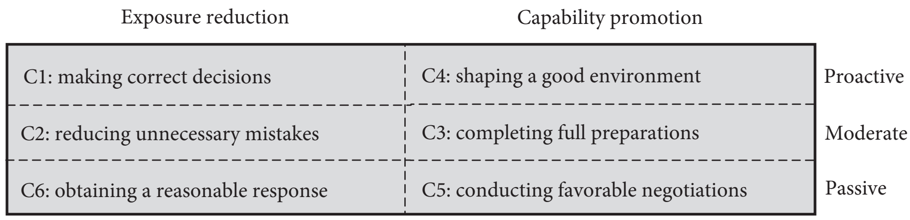

Figure 1: Characteristics of the components.

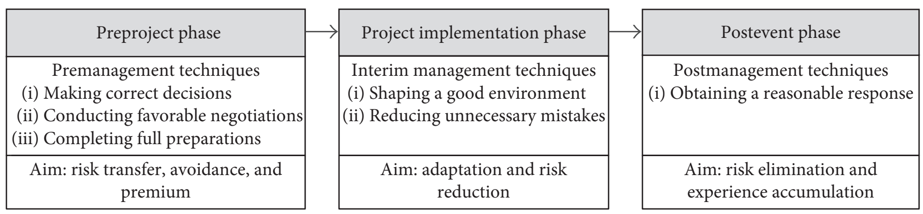

Figure 2: Application of the components.

fluctuations [6]. However, in a low-risk country, ICEs can choose a permanent entry mode (e.g., a sole-venture company, a joint-venture company, and branch offices) [6, 47] to seek further development and higher profits. In choosing projects, ICEs should select those that are suited to their capacities, fit their interests, and utilize their own expertise. In addition, if ICEs choose a project greatly desired by the host governments and the local population, a good operating environment will be established, and less political risk will exist [3]. The relationship between ICEs and host governments is a very important factor that has great potential influence on political risk management [4, 48]. In a politically stable country, ICEs that have a good relationship with host governments can obtain more support and benefits, such as convenient approval procedures, less government intervention, smooth information and communication channels, and sufficient government guarantees. In contrast, in politically unstable countries, a low-involvement strategy with host governments is a better choice and can help ICEs avoid becoming involved in political struggles. Localization is a common strategy in international business and can help ICEs integrate into the host society [6]. ICEs with a high level of localization will be free from discrimination and opposition [7, 49]. ICEs are paying increasing attention to the control of core and critical technologies because the impact of technology on competition between ICEs is increasingly fierce. Moreover, ICEs with core and critical technologies will have an important position and a stronger voice in negotiations with host governments and experience less government interference in the project implementation phase [6, 50].

5.2.2. Conducting Favorable Negotiations (C5). Three strategies are assigned to this component and account for 9.265% of the total variance: (1) adopting optimal contracts (S04), (2) making a higher tender offer (S01), and (3) obtaining the corresponding guarantee (S11). All of these strategies are strongly related to bidding and contract activities during the early stages of a project.

In the business negotiation stage, the first important issue for ICEs is to select internationally accepted standard contracts and exclude contractual clauses and conditions that are not practiced locally [32, 34]. The contract clauses, such as payment terms, liability for a breach of the terms of the dispute resolution clause, intellectual property clauses, force majeure clauses, and confidentiality provisions should be drafted properly since they are the foundation for the execution of the transaction and the settlement of disputes. When a political risk event occurs, the risk premium can potentially compensate for an ICE's losses. Therefore, if ICEs must confront and retain some risks, an increase in the required return can be provided by making a higher tender offer to protect themselves against those risks [33]. Two common methods are used to increase the tender offer: appropriately increasing the price of materials and using adjustment coefficients. Of course, raising the tender offer cannot make up for all the potential losses, and if the price is too high, the probability of winning the bid will decrease [51]. International guarantee regulations are an efficacious remedy for defects in local remedies, international arbitration, and diplomatic protection [52]. ICEs should try their best to come to an agreement with the host government to obtain the proper guarantees to help them restrict improper behaviors by the host government [46, 33], obtain compensation in a timely manner, and avoid increased losses.

5.2.3. Completing Full Preparations (C3). This component explained 11.155% of the total variance and contained four strategies: (1) making contingency plans (S10), (2) sending staff to training programs (S15), (3) allocating extra funds (S26), and (4) purchasing risk insurance (S03), ranking 9th, 21st, 22nd, and 10th, respectively, among the 27 strategies. The four strategies are related to the preparations for risk response and should be performed before the commencement of construction works.

It is sensible for ICEs to have a written contingency plan for potential political risk to protect their own interests and safety [46, 53]. The content of a contingency plan should include (1) risk prediction and analysis, (2) a dispute settlement mechanism, (3) action roles and responsibilities, (4) equipment and tools, and (5) steps and strategies. The cases in Yemen and Libya demonstrate that a good evacuation plan can effectively protect the safety of international contractors, even during a war. Additionally, appropriate training programs (e.g., antigraft, safety, and self-protection programs) should be provided for employees in accordance with the company's code of conduct and safety policies and procedures. Political risk management should be supported by allocating extra funds [32], which can enhance the flexibility of ICEs in an uncertain environment. An increasing number of multinational enterprises are willing to buy political risk insurance, which is considered an important measure to manage political risks. Political risk insurance can reduce the uninsured losses caused by various types of political risk, such as war, internal conflict, transfer restrictions, repudiation of debt, and expropriation [16]. In some cases, political risk is also used as a bargaining chip for companies to secure long-term loans and settle disputes with governments [54]. Political risk insurance can be purchased from three types of providers: (1) public providers such as the African Trade Insurance Agency and the Asian Development Bank, (2) private providers such as the insurance centers in London and the United States, and (3) reinsurers such as Hannover Re (Germany) and the China Export and Credit Insurance Corporation.

5.2.4. Shaping a Good Environment (C4). This component was responsible for 10.817% of the total variance and included four strategies: (1) maintaining good relations with powerful groups (S19), (2) maintaining good relations with the public (S27), (3) linking with local businesses (S20), and (4) building a reputation (S25). These four strategies can help enterprises create a good operating environment in a foreign land.

ICEs should maintain good relations with powerful groups (e.g., the media, labor unions, business coalitions, industry associations, consumer associations, and environmental protection groups) in host countries [3]. Not only are powerful groups important influencers in policy making, but they also play significant roles in the economic and social environment [46]. Good relations with powerful local groups are very helpful for ICEs in terms of obtaining the necessary resources and reducing interference. For example, ICEs can obtain useful market and policy information through partnerships with industry associations and business coalitions [55], but they may suffer from extra checks from labor unions because of disputes with local workers [56]. It is well known that opposition to international construction projects is often initiated by the local public [32]. Therefore, maintaining good relations with the public is beneficial for ICEs in terms of avoiding unnecessary trouble. Linking with local businesses, such as choosing well-connected local business partners or strengthening co-operation with local enterprises, can help ICEs reduce their image as foreigners [46] and therefore reduce their probability of becoming involved in micropolitical processes [8, 49]. Corporate reputation refers to the extent to which an enterprise garners public trust and praise and the extent to which an enterprise influences the public [57]. Corporate reputation represents the sum of a multinational enterprise's ability to obtain social recognition, resources, opportunities, and support and to achieve value creation in the host country. A good reputation can allow ICEs to respond quickly to a crisis and enhance their ability to resist risk. Building a corporate reputation is a long-term process, and hence, ICEs must make unremitting efforts (e.g., taking into account the interests of the local public, participating in local public welfare activities, and cultivating a good image via marketing efforts) to create a good reputation [58, 59].

5.2.5. Reducing Unnecessary Mistakes (C2). This component accounted for 13.587% of the total variance and consisted of five strategies: (1) avoiding misconduct (S06), (2) employing capable local partners (S24), (3) supporting environmental protection (S08), (4) abiding by the local culture (S09), and (5) adopting closed management of the construction site (S07). The strategies in this component are strongly related to the policy of reducing ICEs' unnecessary mistakes in their operations.

Many cases have shown that political risk is closely linked to misconduct (e.g., bribery, legal violations, wages in arrears, dishonest acts, environmental pollution, and cultural conflicts) by ICEs during the project implementation phase [34, 56]. For example, in a very racist country, ICEs' discrimination against certain local people may lead to racial tension, thus causing government interference; in a corruption-ridden country, unhealthy relationships between enterprises and the host government may cause protests or opposition from the public. Thus, ICEs should act strictly according to a code of conduct to eliminate political risk caused by their own mistakes. Cultural conflicts often occur in international marketing practice. Respecting and abiding by the local culture will help ICEs to mitigate the risks arising from cultural conflicts [3, 8]. Environmental protection and sustainable development are currently major trends. Many people as well as governments have increasingly begun to pay attention to environmental protection. Thus, taking part in the protection and construction of the ecological environment will help ICEs maintain good relations with the local population. The market skills and knowledge of experienced and qualified local partners (e.g., lawyers, subcontractors, suppliers, and agencies) are effective supplements for ICEs, especially for ICEs that lack practical market experience in the host country. Employing resourceful local partners can help ICEs not only reduce costs and improve work efficiency but also gain legitimacy under institutional pressure [1, 60]. Closed management of construction sites with security systems (e.g., security guards, monitoring devices, and alarm mechanisms) is an effective means for ICEs to prevent crime, terrorist attacks, and external conflicts, thus keeping sites safe in an unstable environment [5].

5.2.6. Obtaining a Reasonable Response (C6). Strategies clustered in this component are generally associated with risk response when a risk occurs, accounting for 10.155% of the total variance. This strategy contains four strategies: (1) implementing an emergency plan (S12), (2) settling disputes through renegotiation (S16), (3) changing the operation strategies (S21), and (4) conducting a postresponse assessment (S14).

Once political risk events arise, ICEs should immediately implement a risk emergency plan to reduce damage and better protect their security [34]. For example, at the onset of wars, ICEs should promptly contact the embassy, suspend construction work, and evacuate their employees. Organizational capability and flexible adaptability are important weapons that ICEs can use to address difficulties in the emergency plan implementation process. In special cases, ICEs can also seek the support of the general public, local governments, their home countries, international organizations, and the media to cope with intractable threats. After the threat disappears, reassessing the residual risks is an effective means through which ICEs can adjust project plans in terms of resources, schedules, and costs and judge whether there is a need to make a claim, renegotiate, or change the operations strategies [46, 52]. In the course of claims or renegotiations, any disputes should be settled through reasonable channels, such as demanding compensation based on the contract or guarantee treaty, making use of international conventions, or resorting to arbitration or conciliation [54]. It should be noted that successful claims and renegotiations by ICEs are based on adequate evidence of their losses. Therefore, they must protect related documents even in deteriorating situations [5]. Lessons learned from practical project cases are more valuable than those learned from books and can be consolidated through a postresponse assessment. These lessons and knowledge can help ICEs to improve their capacity for political risk management and therefore to effectively address similar political risks in the future.

6. Conclusions

Political risk is a major problem encountered by ICEs in international construction projects. It is thus necessary to identify the strategies that can help ICEs address political risk. On the basis of a comprehensive literature review, 27 possible political risk management strategies were identified. The results of the questionnaire survey indicated that all the strategies were important for political risk management in international construction projects. Five strategies, including (1) choosing suitable projects (S17), (2) building proper relations with host governments (S18), (3) conducting market research (S02), (4) avoiding misconduct (S06), and (5) choosing a suitable entry mode (S23), were the most important strategies according to their average values.

Through the exploratory factor analysis, the 27 strategies were clustered into six components: (1) making correct decisions (C1), (2) reducing unnecessary mistakes (C2), (3) completing full preparations (C3), (4) shaping a good environment (C4), (5) conducting favorable negotiations (C5), and (6) obtaining a reasonable response (C6). The components (C1, C2, and C6) of the exposure decline dimension have higher contributions to political risk management than the components (C4, C3, and C5) of the capacity promotion dimension. In addition, components with a proactive characteristic (C1 and C4), components with a moderate characteristic (C2 and C3), and components with a passive characteristic (C5 and C6) can be ranked from the most to the least important for political risk management according to their cumulative variance.

Furthermore, the six components independently contribute to political risk management in three different phases. In the preproject phase, premanagement techniques (C1, C3, and C5) can help ICEs avoid or transfer unacceptable risks and improve quotes for the retained risk. In the project implementation phase, interim management techniques (C2 and C4) are conducive to reducing risk and promoting ICEs' adaptation to the overseas construction market. In the postevent phase, postmanagement techniques (C6) are useful for ICEs to eliminate their actual risk and to accumulate experience with political risk management. The high cumulative variance of the premanagement strategies indicated that the main tasks of political risk management should be performed in the early stage of a project.

Compared to the respondents in the academic group, who were from different countries, all the respondents in the practitioner group were from Chinese construction enterprises, which is a limitation of this study. Nevertheless, the results of the independent-sample *t*-test revealed no significant differences in the responses between academics and practitioners. In addition, conditions in the global market are typically the same for ICEs from different countries. The relevant experience of the respondents is a reference for all practitioners, regardless of their nationalities. However, the characteristics of different enterprises and the actual conditions in different countries should be carefully considered when implementing these strategies. Further work could focus on evaluating these strategies with samples from different enterprises or different countries to increase the practical validity of the results. Despite its limitations, this study is a useful reference for academics and practitioners in terms of gaining an in-depth understanding of political risk management in international construction projects and provides guidance for ICEs to manage political risk when venturing outside their home countries.

Data Availability

The data from the 127 returned questionnaires used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Critical Success Factors for Safety Management of High-Rise Building Construction Projects in China

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This study aims at identifying the critical success factors (CSFs) for safety management of high-rise building construction projects and exploring interactions among such CSFs. Study data were sourced from semistructured interviews and a questionnaire survey administered in China. The study constructs a third-order CSFs system containing six CSFs: management measures, management organization, technical and management plan, worker safety behavior, safety environment, and worker safety quality. Among these, management organization is found to be the key factor affecting construction safety management performance, while worker safety behavior is a factor with a direct impact. Implications for practice are proposed. This study enriches the existing literature on the CSFs and performance evaluation of construction safety management in high-rise building construction projects. Safety performance of high-rise building construction projects can be effectively enhanced by improving the professional competence of safety management organizations.

1. Introduction

The construction industry remains one of the world's most dangerous industrial sectors, accounting for 30–40% of fatal injuries despite only accounting for around 7% of employment [1]. In Korea, it accounts for the highest proportion (25.3%) of workplace fatalities [2, 3], the third-highest in the U.S. [4], and the fourth-highest in Australia [5]. In China, only the coal-mining industry is more dangerous than construction [6].

Safety performance is a serious challenge in high-rise building construction with high-altitude operation and excavation of deep foundation pits resulting in much higher accident rates and more severe injuries than found in medium- and low-rise buildings. Injuries and fatalities resulted from falls and the impact of falling objects are constant threats. Booming economies and rapid urbanization in East Asia, and in China in particular, have massively increased the volume of high-rise construction in the region. According to the Council on Tall Buildings and Urban Habitat [7], in 2017, China alone accounted for 53% of the world's 200-meter-plus buildings, thus issues related to improving safety performance of high-rise building construction are an urgent concern in China.

This research seeks to identify critical success factors (CSFs) in construction safety management practices for high-rise buildings and to determine mutual interactions between these factors. The remainder of this paper is organized as follows. Section 2 systematically reviews the literature related to CSFs, construction safety management for high-rise buildings, and factors affecting construction safety management. Section 3 reviews research methods using semistructured interviews and a questionnaire survey. Section 4 reports the results and corresponding discussion. Section 5 clarifies the relationships among CSFs. Conclusions and recommendations for future studies are provided in Section 6.

2. Literature Review

2.1. Critical Success Factors. The concept of "success factors" was first developed by Daniel [8] in the context of the importance of information systems. Generally, success in most industries is determined by three to six factors. Rockart [9] wrote that "*CSFs are, for any business, the limited number of areas in which results, if they are satisfactory, will ensure successful competitive performance for the organization*." Thus, CSFs are areas of activity that should receive constant and careful attention from management.

Studies in the field of construction have adopted the CSF approach to examine safety issues. For example, Aksorn and Hadikusumo [10] investigated the CSFs of safety program implementation in medium- and large-scale construction projects in Thailand. Al Haadir and Panuwatwanich [11] explored the critical factors influencing the implementation of safety programs among construction companies in Saudi Arabia. The CSF approach has also been widely adopted in construction partnering [12–14], PPP/PFI [15, 16], knowledge management [17], value management [18], and green building researches [19].

2.2. High-Rise Buildings. No internationally agreed definition exists for "high-rise building." For instance, the *International Conference on Fire Safety in High-Rise Buildings* defined a high-rise as "*any structure where the height can have a serious impact on evacuation*" [20]. In the U.S., the *National Fire Protection Association* regarded a high-rise as being higher than 75 feet (23 meters) or about 7 stories [21]. In China, according to *Technical Specification for Concrete structures of Tall Buildings*, a high-rise building is a residential building of 10 floors or more, or 28 meters or more in height, and other commercial buildings exceeding 24 meters, including mega-high-rise buildings (commercial buildings at least 100 meters tall) [22]. This research adopts China's local definition, which is a wide range of tall buildings including mega-high-rise buildings. The absolute height of high-rise buildings gives rise to a wide range of challenges to construction safety management, including extreme environments on high-altitude floors [23, 24] and complex physiological and psychological impacts on construction workers from working at such elevations [25–27].

Despite the impacts of such issues on the complexity of construction safety management for high-rise buildings, the relevant literature is sparse. Hinze and Raboud [28] examined large building construction projects in Canada (mostly high-rise buildings), seeking to assess the degree to which corporate or project policies and practices influence worker safety, and to identify factors affecting safety performance. Ismail et al. [29] sought to identify safety factors that determine the success of safety management systems for high-rise building construction sites. Prior studies into safety management mechanisms fell short of drawing distinctions between high-rise buildings and medium- and low-rise buildings, and common influential factors and CSFs for the construction safety management of high-rise buildings are yet to be identified.

2.3. Factors Affecting Construction Safety Management. A great deal of construction researches has sought to identify factors impacting the success of safety management.

Table 1: Construction safety management regulations and standards.

Region	Title	Abbr.
China	Standard of construction safety inspection (JGJ59-2011)	[30]
	Regulations on safety production management of construction projects	[31]
	Technical code for safety of temporary electrification on construction site (JGJ46-2005)	[32]
	Standard for the work safety assessment of construction company (JGJ/T77-2010)	[33]
	Technical scheme of high-place construction operation (JGJ80-2011)	[34]
Hong Kong	Factories and industrial undertakings ordinance (FIUO-Cap. 59)	[35]
	Occupational safety and health ordinance (OSHO-Cap. 509)	[36]
Singapore	Code of practice for safety management system for construction worksites (CP79:1999)	[37]
	Factories (building operations and work of engineering construction) regulations	[38]
Japan	Construction occupational health and safety management system (COHSMS) guidelines and COHSMS external system evaluation	[39]

Regulations and standards (Table 1) for construction safety management are also major sources for the identification of influential factors. Table 2 summarizes various factors affecting construction safety management identified in past researches and the corresponding regulations and standards. Previous qualitative and quantitative attempts have been made to determine CSFs for the construction industry, with various authors identifying positive or negative relationships between them. However, to date, no research has sought to identify CSFs for high-rise building construction project safety management, constituting a serious gap in the literature.

3. Research Methodology

This study applies a two-pronged research design. First, expert interviews were conducted to develop and validate the initial questionnaire to identify the success factors (SFs) of safety management for high-rise building construction projects based on the factors summarized in Table 2. Second, a questionnaire survey was administered to quantitatively identify CSFs and their interactions.

3.1. Expert Interview. Expert interviews were carried out to validate the constructed questionnaire for SFs for high-rise building construction project safety management. Seven experienced practitioners were interviewed including four safety officers, two engineers, and one project manager, each with at least ten years of work experience in the field of high-rise building construction safety management (Table 3). To guarantee interview comprehensiveness, each lasted 40–60

Table 2: Factors affecting construction safety management.

Number	Factor	Source	Description
1	Safety production liability system	[30, 31]	Safety production liability system is a compulsory system in the Chinese construction industry used to stipulate responsibilities of the leadership, management, and labor layers. Clear assignment of responsibilities enables all involved parties to perform specific tasks to meet safety requirements.
2	Special construction plans for safety of danger subprojects	[30, 31]	High-risk subprojects, such as high-altitude construction, high formwork, and deep foundation pits, need special safety construction plans prior to work. Appropriate special construction plans are essential technical documents used to guide management and operations.
3	Safety inspection	[28, 30, 31, 35, 37, 40–45]	Safety programs may require safety managers (e.g., safety supervisor, project manager, and safety officer, etc.) to conduct adequate inspection during construction to protect workers from workplace hazards. Safety inspections are also an effective way to discover potential safety problems and correct them to reduce the accident rate.
4	Safety education and training of workers	[10, 11, 30, 31, 35, 37, 40, 42, 43, 43–48, 48, 49–52]	Safety management performance can be improved if all workers are educated and trained properly. Education and training are used to improve worker safety awareness and knowledge and skills to prevent accidents.
5	Emergency response plan	[30, 35, 37, 39]	In the event of an accident, emergency rescue is the most efficient way to minimize loss. Thus, construction projects should have scientific emergency response plans in place prior to work.
6	Employment with certificates	[30, 31]	The Chinese construction industry has implemented an occupational certificate system to guarantee worker quality and competence. Safety managers (e.g., project manager, supervisor, and safety officer) and technical workers (e.g., welder, scaffolder, and concreter) are required to obtain professional certification to perform work.
7	Accident reports and investigation	[30, 31, 35, 37, 39, 43, 44, 46, 47, 53]	Accident reports and investigations ensure that accidents are handled appropriately and prompt reflection and improvement. Accident analysis identifies root causes to improve future accident prevention.
8	Safety environment	[30, 31, 37]	Safety environment covers a wide scope including physical environment (e.g., light and temperature), site layout, and safety protection. A good safety environment guarantees safe conditions to reduce potential onsite hazards.
9	Control of subcontractor	[30, 35, 37, 44, 46, 47, 53]	Safety management is not assigned to a single party, but rather is the common purpose of all stakeholders. Subcontractor management entails ensuring subcontractor qualification and performance to ensure safe work practices at all levels.

Table 2: Continued.

Number	Factor	Source	Description
10	Safety committee	[31, 35, 37–39]	Safety committee comprises of the project manager, safety officers, and other relevant management personnels. As the key leader and decision-maker for safety management, the safety committee plays an important role in improving safety performance.
11	Safety incentive	[42–49]	Safety incentives are widely used to incentivize workers to play an active role in safety management and effectively encourage good safety behavior.
12	Regular safety meetings	[28, 41–43, 45, 47]	Regular formal safety meetings allow all relevant parties to review safety records and discuss safety problems. Detailed safety management plans and safety goals should be discussed and determined through such meetings.
13	Management support	[10, 11, 40, 45, 48, 51, 54–57]	Management support can ensure that sufficient resources are allocated for safety management, and proper actions are conducted to improve safety performance. Support from management is also an important dimension of safety climate and safety culture to encourage workers to attach more importance to safety.
14	Provision of personal protection equipment (PPE)	[44, 49, 54, 55]	PPE is essential for routine construction works, and for high-altitude works in particular. In practice, managers should provide adequate PPE to each worker and require its usage.
15	Detailed safety management plan	[42, 46, 47, 53]	The safety management plan is a formal safety management document including safety goals, strategies, measures, rules, and schedules.
16	Safety investment	[40, 42, 48, 55]	Safety investment entails the distribution and allocation of key resources for construction safety management. Safety management cannot be effective without adequate investment. Thus, a certain proportion of engineering costs should be allocated to safety management.
17	Personal attitude	[10, 11, 51, 56, 58]	Personal attitude entails the intrinsic motivation of workers to actively participate in safety management practices. One of the main purposes of safety management is to cultivate positive safety attitudes among workers.
18	Suitable supervision	[10, 11, 51, 56]	Appropriate supervision from government agencies should guarantee the provision of adequate safety resource and standardized management. Supervising departments will regularly inspect construction sites to ensure safety management conforms to relevant regulations and standards.
19	Safety equipment	[10, 51, 52, 56]	The procurement, maintenance, and operation of safety equipment must all be emphasized. The safety of construction site equipment, including cranes, welders, and rebar cutters, must all be strictly controlled.

Table 2: Continued.

Number	Factor	Source	Description
20	Personal competency	[10, 51, 52, 59]	Personal competency means that people can complete tasks properly based on his/her knowledge, experience, and skills. To avoid accidents, tasks must be assigned to qualified individuals.
21	Clear and reasonable objective	[10, 11, 51, 60]	Clear and reasonable safety goals are the main directions for safety management of a project. Safety management strategies, such as plans, schemes, and detailed measures, all should aim to achieve the project safety goals.

minutes and proceeded through three steps: a brief introduction of the research background and objectives, followed by comments on the complexity of construction safety management for high-rise buildings, and verification of each listed variable and proposed modification suggestions.

Feedback gathered from the expert interviews was used to revise the initial questionnaire. Additional influential factors were added including electrical safety, coordinator of special operations (e.g., hoisting and grouting), safety and technology disclosures, daily safety records, adjustable timetables, efficient rectification and reform, worker compensation insurance, safety awareness, sufficient quality of material and equipment, worker awareness and behavior, labor-management relations, and safety climate. Factors that did not fit the Chinese high-rise building construction context were removed, such as extra compensation for high-risk work. Some factors were subdivided. For example, safety environment was divided into safe monitoring, site layout, and physical environment; worker behavior was broken down into stability, peer cooperation, and compliance.

3.2. Questionnaire Survey. A questionnaire survey was designed to collect data. The final questionnaire comprised three parts: (1) project background, used to collect project information, such as building height, type, and safety performance; (2) demographic information of respondents including service experience, qualification certificates, and number of high-rise building construction projects worked on to ensure respondents qualification; and (3) SFs of construction safety management for high-rise buildings. The final questionnaire of part (3) alone included 38 structural questions representing 38 SFs for the safety management of high-rise building construction projects. The questionnaire was constructed using a five-point Likert scale where 1 stands for no influence, 3 stands for moderate influence, and 5 stands for very high influence.

The questionnaire survey was administrated to construction safety personnels who had qualification certificates for safety management and experience in high-rise building construction projects. Construction safety personnels are those with responsibility for overall construction site safety, including safety directors, managers, supervisors, officers, and foremen. In the Chinese construction industry, qualification certificates for safety management include Certified

Table 3: Experts profile.

Number	Role	Service company	Service years
1	Project manager	Contractor	16~20
2	Safety officer	Contractor	11~15
3	Safety officer	Contractor	≥21
4	Safety officer	Contractor	≥21
5	Safety officer	Contractor	16~20
6	Engineer	Owner	11~15
7	Engineer	Supervision department	11~15

Safety Engineer, Safety Officer (including level A, B, and C), Constructor (including Constructor and Associate Constructor), Technician Certificate, and Supervising Engineer (including Registered Supervisor Engineer, Professional Supervisor Engineer, and Supervisor). Prior to the distribution questionnaire, item analysis was applied to the pretest questionnaire to assess the discriminability of questions. As a result, 36 structural questions representing 36 SFs were retained.

A total of 410 questionnaires were distributed to safety management personnels of high-rise building construction projects in person, by post or by email. One hundred and ninety-seven valid questionnaires were collected, giving a response rate of 53.53%. Referring to Figure 1, 90.29% of the valid questionnaires were from male respondents. More than half of the respondents had at least six years of high-rise building construction work experience, and about 30% had been involved in more than five high-rise building construction projects. About 60% of the respondents work primarily on residential high-rise building construction projects, of which more than four-fifths exceeded 17 floors. Forty of the valid questionnaires were received from project owners, while another 40 were from consultants, and the remaining 114 were from contractors. Over 40% of the respondents had received various professional licenses (i.e., qualification certificates) from the relevant Chinese authorities.

4. Extracting Success Variables

4.1. Exploratory Factor Analysis. Exploratory factor analysis (EFA) was applied to uncover the underlying structure of

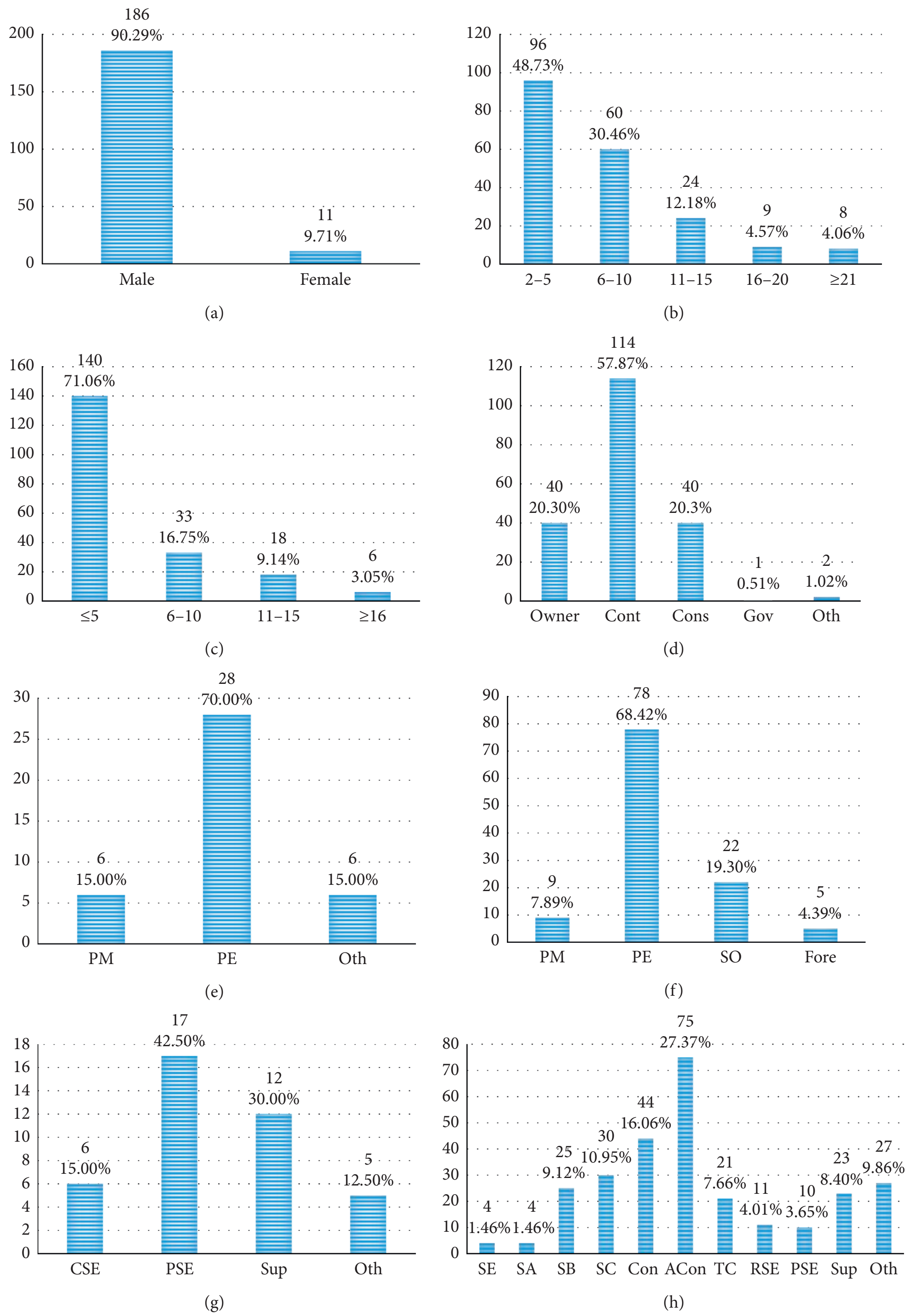
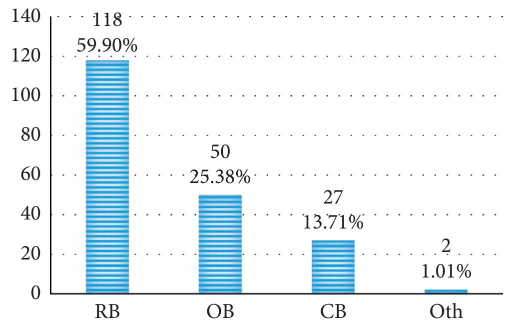
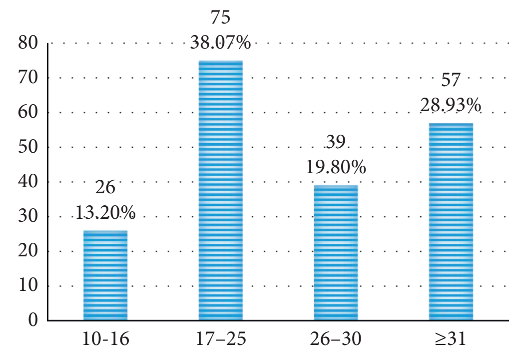


Figure 1: Continued.



(i)



(j)

Figure 1: Respondent demographic data. (a) Gender. (b) Working experience (year). (c) Number of projects involved in. (d) Firm. (e) Owner. (f) Contractor. (g) Consultant. (h) Qualification certificates. (i) Building type. (j) Building height (floors).

variables within questionnaire to identify initial CSFs. Various tests were required to check whether the data could meet EFA requirements, and a correlation matrix was generated to determine correlations among variables. The relationships with high-correlation coefficients (greater than 0.5) were summarized as follows: *Safety committee established* with *Professional competence of safety committee*, *Professional competence of safety committee* with *Safety committee establishes good safety climate*, *Labor-management safety communication* with *Labor-management trust relationship* and *Safety committee establishes good safety climate*, *Labor-management trust relationship* with *Safety committee establishes good safety climate*, *Safety committee establishes good safety climate* with *Safety propaganda*, *Labor-management trust relationship* with *Safety committee establishes good safety climate*, *Worker safety awareness* with *Worker safety knowledge*, *Worker safety knowledge* with *Worker experience*, *Workers obey management* with *Worker cooperation on safety*, *Safety technical measurements in construction organization plan* with *Special construction plans for safety of danger subprojects* and *Detailed safety management plan*, *Worker compensation insurance* with *Emergency response plan* and *Accident/incident reports and investigation*, *Daily safety records* with *Regular safety meetings*, and *Emergency response plan* with *Accident/incident reports and investigation*.

The Bartlett's score for questionnaire sphericity is 3288.275, and the associated significance level is 0.000, indicating that the correlation matrix is not an identity matrix [61]. The Kaiser-Meyer-Olkin (KMO) measure of all the variables is 0.858, which is significantly greater than 0.5 and can be considered highly acceptable. Test results confirmed that the sample data are appropriate for processing EFA. EFA was processed using principal component analysis and promax rotation to identify the initial CSFs (iCSFs), where items exhibiting low communality value (<0.5), low factor loadings (<0.45), and cross-loading were candidates for elimination [61]. The promax rotation is an oblique rotation approach capable of obtaining solutions using correlated components. This approach is commonly applied in almost all fields of social science, as typically each factor is to some extent related to other factors [62]. The promax rotation was realized mainly because the success factors proposed by this study (classified in the social sciences) are mutually dependent to some degree. Table 4 shows the results of final stage EFA. Through the rule of eigenvalue greater than one, the seven-factor solution was considered the most appropriate. The Cronbach's α values for all seven iCSFs exceed 0.65. Every iCSF is named according to its associated success factors as follows: *management measures* (iCSF1), *management organization* (iCSF2), *technical and management plan* (iCSF3), *worker safety behavior* (iCSF4), *guarantee and supervision mechanism* (iCSF5), *safety environment* (iCSF6), and *worker safety quality* (iCSF7).

4.2. Confirmatory Factor Analysis. Confirmatory factor analysis (CFA) was used to determine the final CSFs framework. Overall model fitness is examined using goodness-of-fit (GOF) indices. According to Table 5, the final measurement model fits the data exactly. Figure 2 shows the final CSF system with path coefficients. As shown in Figure 2, at the third-order level, there were two groups (*Organizations and Strategies*, *Environment and Workers*) including six CSFs which were measured by 12 observed variables.

The second-order groups were structured according to first-order data statistical characteristics (correlation coefficients), existing research results, and practical experience. In the first-order measurement model, the correlation coefficients of *worker safety behavior (CSF4)* with *worker safety quality (CSF7)* and *safety environment (CSF6)* are 0.53 and 0.45, respectively, exceeding the moderate correlation level. Thus, we grouped CSF4, CSF6, and CSF7 into one second-order structure named "*Environment and Workers*." Furthermore, the correlation coefficients of *management measures (CSF1)* with *management organization (CSF2)* and *technical and management plan (CSF3)* (0.51, 0.50) and *management organization (CSF2)* with *technical and management plan (CSF3)* (0.41) exceed the moderate correlation level. In practice, safety committees are responsible for compiling and auditing technical and management schemes, as well as for implementing management policies. Thus, CSF1, CSF2, and CSF3 were grouped together and named "*Organization and Strategies*."

Table 4: Initial CSFs.

Cluster	Success factor	Communality value	Factor loading	Cronbach's α	Factor label
iCSF1	SF27. Daily safety records	0.694	0.833	0.835	Management measures
	SF28. Regular safety meetings	0.610	0.772		
	SF29. Safety education and training of workers	0.514	0.767		
	SF25. Safety and technology disclosure	0.626	0.608		
	SF32. Emergency response plan	0.713	0.519		
	SF33. Accident/incident reports and investigation	0.665	0.513		
iCSF2	SF7. Safety committee established	0.673	0.778	0.751	Management organization
	SF9. Management support	0.619	0.739		
	SF8. Professional competence of safety committee	0.684	0.713		
iCSF3	SF20. Special construction plans for safety of danger subprojects	0.684	0.859	0.792	Technical and management plan
	SF19. Safety technical measurements in construction organization plan	0.744	0.825		
	SF21. Detailed safety management plan	0.692	0.710		
iCSF4	SF18. Worker cooperation on safety	0.644	0.791	0.717	Worker safety behavior
	SF16. Low worker mobility	0.625	0.776		
	SF17. Workers obey management	0.613	0.658		
iCSF5	SF5. Electrical safety	0.583	0.771	0.663	Guarantee and supervision mechanism
	SF6. Equipment safety	0.565	0.702		
	SF24. Safety investment	0.605	0.586		
	SF34. Safety-related rewards and punishments	0.595	0.479		
	SF23. Worker compensation insurance	0.634	0.451		
iCSF6	SF2. Tidy worksite	0.593	0.746	0.658	Safety environment
	SF3. Good physical environment	0.549	0.632		
	SF4. Sufficient quality of material and equipment	0.624	0.586		
	SF1. Provision of PPE	0.609	0.523		
iCSF7	SF13. Worker safety awareness	0.771	0.819	0.806	Worker safety quality
	SF14. Worker safety knowledge	0.743	0.806		

In the group *Organizations and Strategies* (group 1), *management measures* ($\lambda = 0.804$) play the greatest role, followed by *technical and management plan* ($\lambda = 0.670$) and *management organization* ($\lambda = 0.648$). This is attributed to the complexity of high-rise building construction requiring corresponding measures and strategies to manage workers and the worksite. *Management measures* was measured by safety meetings ($\lambda = 0.702$) and safety training ($\lambda = 0.663$), showing that safety meetings and training are basic management measures. *Technical and management plan* refers to the detailed safety technical measurements ($\lambda = 0.788$) and management plan ($\lambda = 0.762$) in construction organization scheme. Some complex subprojects of high-rise buildings, such as foundation pit, formwork, and scaffold, may require appropriate technical and management planning for guidance. *Management organization* entails the establishment of a safety committee ($\lambda = 0.794$) and the professional competence of committee members ($\lambda = 0.837$). This result is consistent with the work of Sawacha et al. [54], who identified safety committee policy as a significant influence factor on construction safety performance.

In the group *Environment and Workers* (group 2), *worker safety behavior* ($\lambda = 0.912$) is found to have the greatest influence, followed by *safety environment* ($\lambda = 0.577$), while *worker safety quality* ($\lambda = 0.549$) is the least influential factor. The high impact of *worker safety behavior* is consistent with the findings of Blackmon and Gramopadhye [63] who argued that 98% of construction accidents could be attributed to unsafe human behavior. *Worker safety behavior* was measured according to worker safety cooperation ($\lambda = 0.723$) and low worker mobility ($\lambda = 0.655$). Fang et al. [42] and Ismail et al. [29] both highlighted the significant role of cooperation played in construction safety, including cooperation among workers, as well as cooperation between workers and managers. In addition, relatively stable worker status could lower the likelihood of accidents. The positive relationship between worker stability and safety performance has been verified by Fang et al. [42] and Cheng et al. [40]. *Safety environment* requires tidy worksite ($\lambda = 0.650$) and sufficient quality of material and equipment ($\lambda = 0.618$). *Worker safety quality* comprises safety awareness ($\lambda = 0.794$) and safety knowledge ($\lambda = 0.854$), which form workers' intrinsic motivation to operate safely.

Table 5: GOF indices of CSFs measurement model.

GOF indices	Suggested level	CSF measurement model	Results
χ^2 (p)	The least ($p \geq 0.05$)	67.888 (0.082)	OK
χ^2/df	≤ 3	1.281	OK
GFI	>0.9	0.948	OK
AGFI	>0.9	0.923	OK
RMR	<0.05	0.036	OK
RMSEA	<0.05	0.038	OK
NFI	>0.9	0.901	OK
CFI	>0.9	0.976	OK

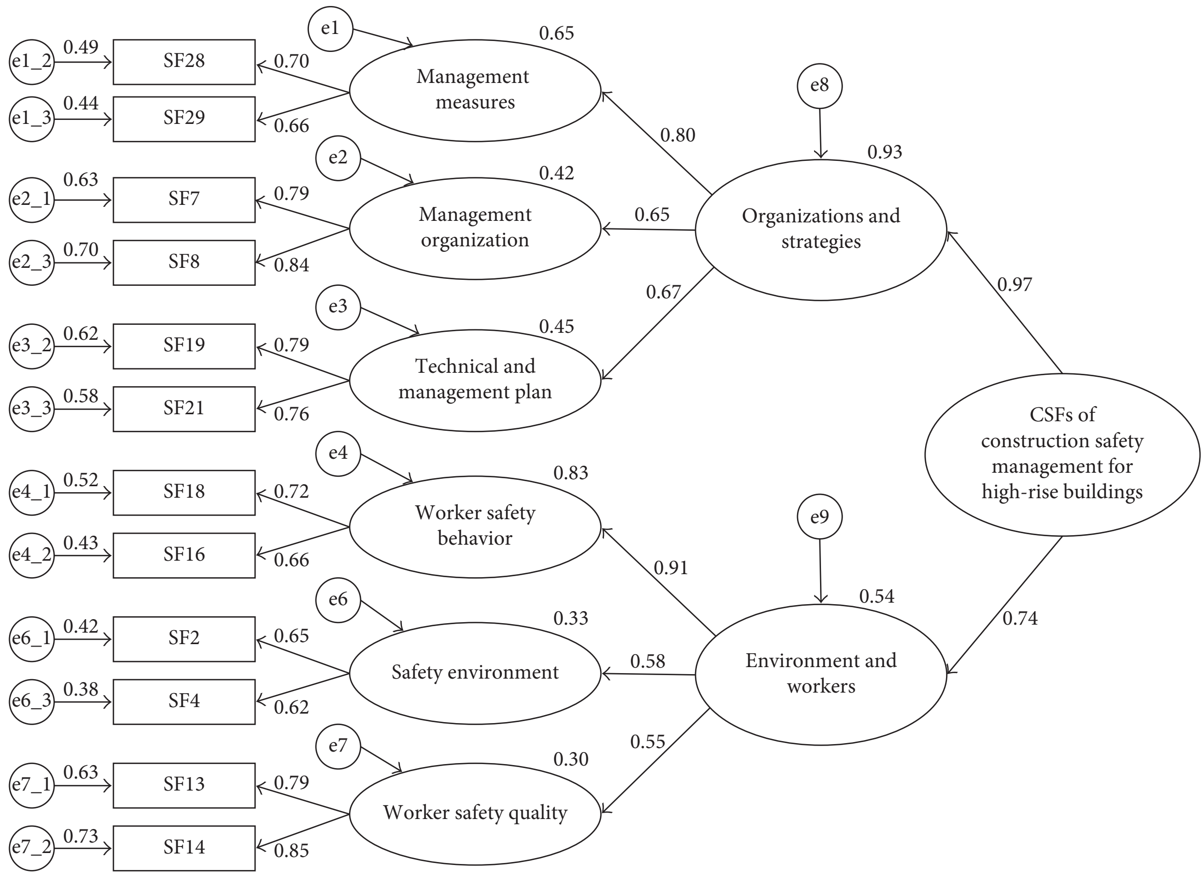


Figure 2: CSF measurement model.

5. Clarifying the Relationships among CSFs

The SEM structural model was used to test interactions among CSFs. To construct the basic framework, the hypotheses describing relationships among CSFs should first be set up on the basis of theoretical expectations and past empirical findings.

5.1. Hypothesis Development. Accident causation theories provide a theoretical basis for hypotheses development. At the early stage, several domino theories were used to analyze accident causation and their relations, including those proposed by Heinrich and Granniss [64] and Bird et al. [65]. Heinrich and Granniss [64] argued that deficiencies in human behavior might lead to accidents, whereas unsafe behavior was caused by worker shortcomings and failure, stemming from both nature (e.g., impertinency, stubbornness, and nervousness) and nurture (e.g., lack of safety knowledge and poor safety awareness). This argument was supported by Bird et al. [65] whose domain theory considered personal reasons that lead to inappropriate behavior. Lack of safety knowledge, safety awareness, and work skills could be regarded as personal reasons. Thus, we develop a hypothesis that *worker safety quality* (CSF7) positively affects their *safety behavior* (CSF4).

In Bird et al.'s domino theory [65], the direct causes of accidents are unsafe conditions and unsafe human behavior, whereas the root cause of accidents is management defects. This suggests that management deficiencies may negatively impact the safety environment and human safety behavior, resulting in accidents. Therefore, the following hypotheses are proposed regarding relations between management factors, the safety environment and safety behavior: (a) *management measures* (CSF1) positively affects *worker safety behavior* (CSF4); (b) *management measures* (CSF1) positively affects *safety environment* (CSF6); and (c) *technical and management plan* (CSF3) positively affects *worker safety behavior* (CSF4).

Trace intersection theory states that workplace accidents are the result of a combination of unsecure environment and unsafe behavior, meaning the traces of the safety environment and worker behavior may intersect to cause accidents. Thus, we propose that *safety environment* (CSF6) positively affects *worker safety behavior* (CSF4).

In addition to accident-causing theories, a large number of empirical studies have modeled the relations of influential factors of construction safety performance. Xing et al. [66] found that organizational factors, such as safety culture and leadership capacity, along with regulator and personnel arrangements, have a direct effect on management measures (e.g., safety checks and safety protection). Consequently, it is hypothesized that *management organization* (CSF2) positively affects *management measures* (CSF1).

In practice, safety committees take charge of compiling and auditing the technical and management scheme, as well as the

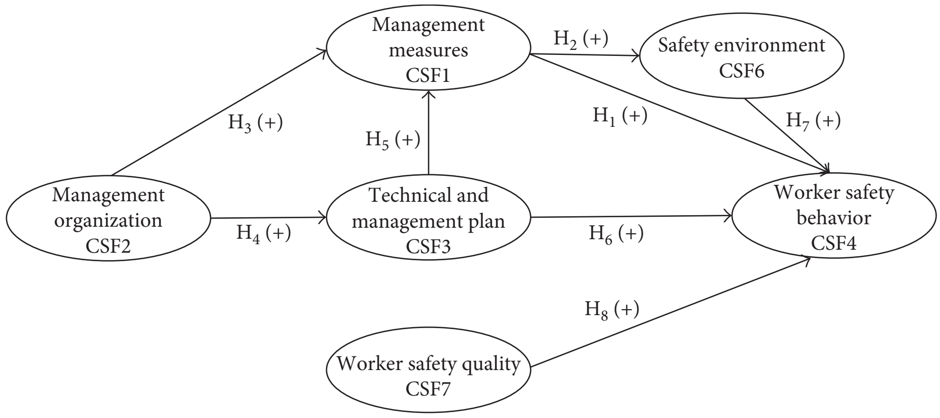


Figure 3: Initial CSF structural model.

Table 6: GOF indices of CSF structural models.

GOF indices	Suggested level	Initial model	First revised model	Second revised model (final)
χ^2 (p)	The least $(p \geq 0.05)$	*81.236 (0.006)*	67.781 (0.058)	68.235 (0.065)
χ^2/df	≤3	1.562	1.329	1.312
GFI	>0.9	0.939	0.948	0.948
AGFI	>0.9	0.909	0.921	0.922
RMR	<0.05	*0.055*	0.038	0.038
RMSEA	<0.05	*0.054*	0.041	0.040
NFI	>0.9	*0.881*	0.901	0.900
CFI	>0.9	0.953	0.973	0.974

Number italicized means it fails to meet the suggested levels.

implementation of management measures. Thus, the following hypotheses are established: (a) *management organization* (CSF2) has a positive impact on *technical and management plan* (CSF3); and (b) *technical and management plan* (CSF3) has a positive impact on *management measures* (CSF1).

As shown in Figure 3, the hypotheses proposed in this study are summarized as follows:

H_1: *management measures* (CSF1) positively affects worker *safety behavior* (CSF4).

H_2: *management measures* (CSF1) positively affects *safety environment* (CSF6).

H_3: *management organization* (CSF2) positively affects *management measures* (CSF1).

H_4: *management organization* (CSF2) has a positive impact on *technical and management plan* (CSF3).

H_5: *technical and management plan* (CSF3) has a positive impact on *management measures* (CSF1).

H_6: *technical and management plan* (CSF3) positively affects *worker safety behavior* (CSF4).

H_7: *safety environment* (CSF6) positively affects *worker safety behavior* (CSF4).

H_8: *worker safety quality* (CSF7) positively affects their *safety behaviors* (CSF4).

5.2. Structural Model Evaluation and Hypothesis Testing. The structural model was tested by SEM path analysis. GOF indices were used to examine the overall fitness. If the GOF indices do not reach the recommended levels, model modification was required to improve overall fitness according to the modified index (MI). Model refinement was also performed in response to insignificant correlation coefficients.

Table 6 summarizes suggested levels of GOF indices and the indices of the initial and final structural models. Four indices of the initial model, χ^2, RMR, RMSEA, and NFI, failed to meet the suggested levels, indicating the need for model modification. The first revised model added the relation path of *management organization* (CSF2) and *worker safety quality* (CSF7). Although GOF indices of the first revised model met the requirements, the model should also be modified because of the insignificant path (standardized weight = 0.14; $p = 0.498$) between *management measures* (CSF1) and *worker safety behavior* (CSF4). As shown in Figure 4, after deleting the relation path of CSF1 and CSF4, the GOF indices of the final structural model reached the threshold levels. Referring to Table 7, in addition to the nonoriginal hypothesis (CSF7 ← CSF2), seven path coefficients have a p value lower than 0.01, indicating they are statistically significant at the 0.01 level, suggesting that seven of the hypotheses (i.e., H_2, H_3, H_4, H_5, H_6, H_7, and H_8) are supported. One of the eight hypotheses (H_1) was dismissed, and the other seven proved meaningful.

The rejection of H_1 was unexpected. Generally, construction safety management personnels govern the worker safety behavior through certain safety management measures. In most cases, CSF1 should have a direct impact on CSF4. However, in this study, the two observed variables (SF28 and SF29) included in CSF1 are mainly intended to

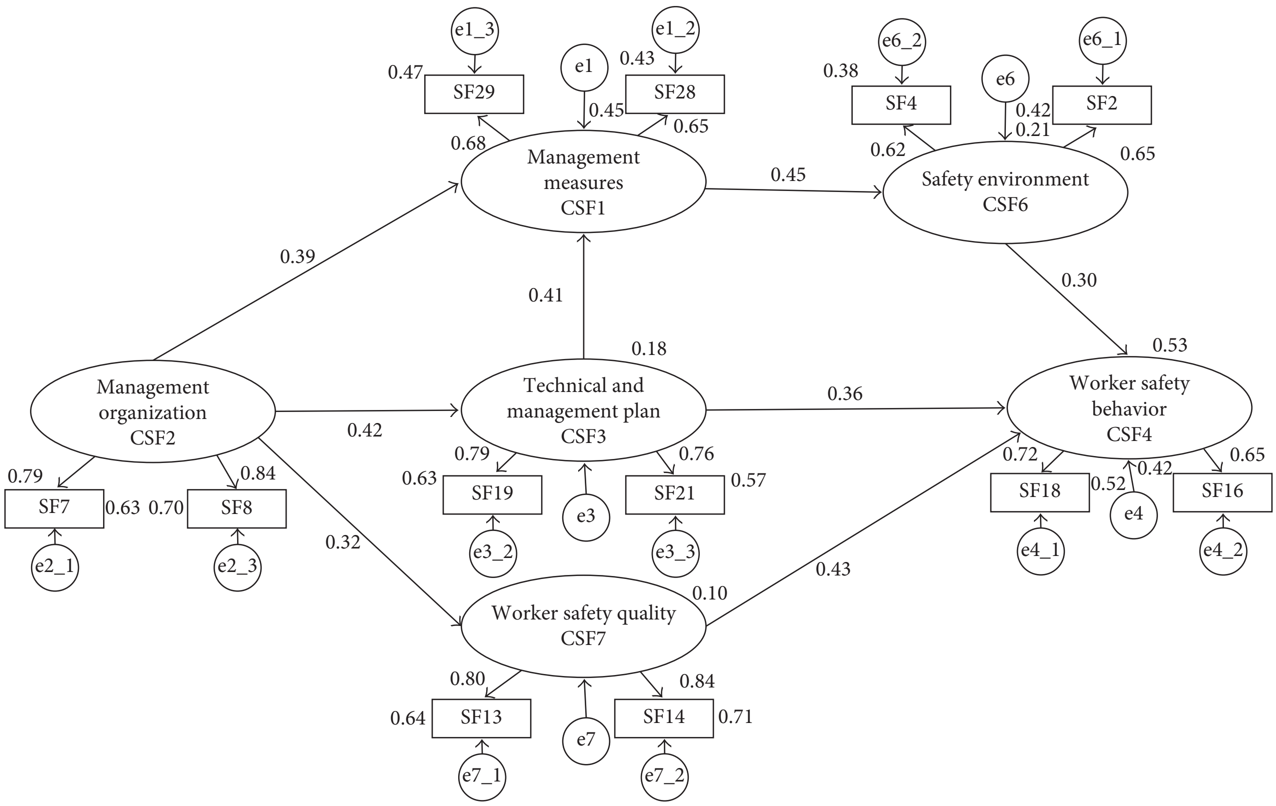


Figure 4: Final CSF structural model.

improve worker safety awareness and safety knowledge. Such measures aim to create a better jobsite safety environment, and further create a good safety climate, rather than directly regulate worker behavior. Due to the characteristics of high-rise building construction, CSF4 also affects the direct interaction between CSF1 and CSF4 to a certain extent. Although path analysis showed no direct effect between CSF1 and CSF4, it does not necessarily mean that CSF1 does not regulate CSF4. In fact, CSF1 indirectly affects CSF4 via *safety environment* (CSF6), as shown in Figure 4.

5.3. Analyzing the CSFs

5.3.1. Management Organization (CSF2). Management organization (CSF2) is considered to be the fundamental factor that has both direct and indirect relationships with other CSFs. Three significant correlation paths between *management organization* (CSF2) and *management measures* (CSF1), *technical and management plan* (CSF3), as well as *worker safety quality* (CSF7) indicate that management organization has direct effects on management measures, technical and management plans, and worker safety quality. The safety committee, as the implementer and supervisor of safety management, exerts decision-making power over the technical and management plan and management measures.

As the implementation of concrete measures should comply with the technical and management plan, and be supervised by safety committee, *management organization* (CSF2) also has an indirect effect on *management measures* (CSF1) through the *technical and management plan* (CSF3). One of novel results of this study is that *management organization* (CSF2) is found to directly influence *worker safety quality* (CSF7). Since the safety management committee provides workers with resources to control accidents and achieve safety goals, the education and training organized by safety committee enable workers to enhance safety quality, competency, and skills [67].

As for indirect effects, *management organization* (CSF2) affects *safety environment* (CSF6) through *management measures* (CSF1) and the *technical and management plan* (CSF3), thus improving management measures, and the technical and management plan will allow safety management organizations to enhance construction environment safety. Through the *technical and management plan* (CSF3), *management organization* (CSF2) indirectly impacts *worker safety behavior* (CSF4). Ultimately, the main purpose of construction safety management is to control worker behavior and protect them from accidents. Thus, safety management organization will control human behavior by providing the scientific, technical, and management plan.

5.3.2. Technical and Management Plan (CSF3). The relationships between the *technical and management plan* (CSF3) with *management measures* (CSF1) and *worker safety behavior* (CSF4) are shown to be significant. As the basic guideline for safety management, the technical and management plan may stipulate detailed management measures, such as training schemes and safety meeting systems. Since

Table 7: Path coefficients and significant test of the final model.

Hypotheses	Relationship	Standardized weight	Estimate	S.E.	C.R.	p value	Test result
H_1	CSF4 ← CSF1	0.104	0.120	0.178	0.678	0.498	Reject
H_2	CSF6 ← CSF1	0.463	0.484	0.124	3.896	***	Support
H_3	CSF1 ← CSF2	0.393	0.305	0.080	3.796	***	Support
H_4	CSF3 ← CSF2	0.423	0.413	0.086	4.821	***	Support
H_5	CSF1 ← CSF3	0.405	0.323	0.085	3.800	***	Support
H_6	CSF4 ← CSF3	0.361	0.335	0.091	3.661	***	Support
H_7	CSF4 ← CSF6	0.302	0.337	0.130	2.598	**	Support
H_8	CSF4 ← CSF7	0.429	0.441	0.092	4.813	***	Support
Nonoriginal	CSF7 ← CSF2	0.320	0.283	0.076	3.727	***	Support

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

human behavior is a main direct cause of safety accidents, the technical and management plan will also directly stipulate modes of work operations and behavior.

The results found that the *technical and management plan* (CSF3) indirectly affects *safety environment* (CSF6). In practice, a construction organization scheme provides detailed management measures, some of which will influence onsite conditions, which accounts for the indirect impact of the *technical and management plan* (CSF3) on the *safety environment* (CSF6). In addition, the technical and management plan might also implement measures to effectively control human behavior and enhance worksite safety.

5.3.3. Management Measures (CSF1). *Safety environment* (CSF6) is directly influenced by *management measures* (CSF1), indicating that appropriate safety management measures can improve the worksite safety environment. Through safety meetings and trainings, quality requirements can be made explicit for workers using plans and proper locations of material and equipment. *Management measures* (CSF1) slightly affects *worker safety behavior* (CSF4) through the *safety environment* (CSF6). This indicates that implementing safety management measures will influence worker behavior through enhancing the worksite environment.

5.3.4. Worker Safety Quality (CSF7). *Worker safety quality* (CSF7) directly impacts *worker safety behavior* (CSF4). As Heinrich and Granniss [64] and Bird et al. [65] suggested, human factors (e.g., lack of appropriate safety knowledge, awareness, and talent) are the underlying causes of misconduct which can result in accidents. Thus, it is reasonable that worker safety awareness and knowledge will directly impact their worksite behavior.

5.3.5. Safety Environment (CSF6). *Safety environment* (CSF6) is found to significantly influence *worker safety behavior* (CSF4), which is consistent with the findings of Chi et al. [68] who indicated an interrelationship among safety behavior and safety environment through a review of 9,358 construction safety accidents in the US. Chi et al. [68] explained that, combined with certain unsafe working conditions, unsafe worker behavior is the major root cause of accidents. In other words, the negative consequence of unsafe behavior can be intensified by unsafe conditions.

5.3.6. Worker Safety Behavior (CSF4). Safety behavior means personal actions taken for self-protection, such as following safety regulations to prevent danger to oneself or others and wearing protective gear [69, 70]. Safety behavior is not only directly affected by sincerity, openness, and extroversion but also is indirectly affected by stress reactions, safety motivation, and safety knowledge [71]. Unsafe behavior is the leading direct cause of safety accidents, and safety behavior has a negative effect on the frequency of occupational injury [72]. In fact, over 98% of construction accidents could be attributed to unsafe behavior [63]. This study found that *worker safety behavior* (CSF4) is directly and indirectly influenced by each of the proposed CSFs in high-rise building construction projects in China. Thus, *worker safety behavior* (CSF4) can be seen as the leading direct factor for determining construction safety performance in high-rise building construction projects.

6. Conclusions

High-rise building construction is a complex process, influenced by numerous and variable factors. Excellent safety management performance plays an essential role in construction project success. This study identified CSFs for safety management of high-rise building construction projects (objective one) and explored interactions among them (objective two). Expert interviews and a questionnaire survey were used to collect data for high-rise building projects in China. This study differs from previous work by focusing on the CSFs for safety management of high-rise building construction projects and their interrelationships. The study also provides an important reference for safety management personnels on high-rise building construction projects.

For objective one, this study established six third-order CSFs including *management measures* (CSF1), *management organization* (CSF2), *technical and management plan* (CSF3), *worker safety behavior* (CSF4), *safety environment* (CSF6), and *worker safety quality* (CSF7). Among these, the first three are grouped into *Organizations and Strategies* (group 1), and the latter three are grouped as *Environment and Workers* (group 2). In terms of impact, *management measures* (CSF1) has the strongest effect in group 1, and *worker safety behavior* (CSF4) is the strongest in group 2. *Management measures* (CSF1) is the most representative CSF, followed by *worker safety behavior* (CSF4). In terms of objective two, interactions among the CSFs show that *management organization* (CSF2) is the fundamental factor affecting construction safety management performance of high-rise buildings because it has the largest total effect on the other CSFs. Conversely, *worker safety behavior* (CSF4) is influenced by other CSFs but does not impact others, indicating that CSF4 is a direct-acting factor for the construction safety management performance of high-rise buildings.

The research findings have both theoretical and practical implications. In terms of theoretical contributions, this study enriches the existing literature on the CSFs and performance evaluation of construction safety management in high-rise buildings. The practical implication is that safety performance of high-rise building construction can be effectively enhanced by improving the professional competence of safety management organizations. Project owners and contractors should assign professional safety management personnels to establish a safety committee. At the same time, managers should adopt measures including safety training and safety meetings to enhance worker safety awareness and promote correct safety behavior.

This study takes a broad view of high-rise building construction projects (including mega-high-rise building construction); thus, further investigation is needed to identify specific characteristics of different types of high-rise building construction projects. Future work could seek to differentiate CSFs for construction of general high-rise buildings and mega-high-rise buildings. In addition, case studies for high-rise building construction projects could be conducted to extend the research findings.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Individual, Group, and Organizational Factors Affecting Group Bidding Decisions for Construction Projects

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Deciding whether bid for the construction project is classic risk-based decision-making that is crucial to the survival and prosperousness of construction companies. More contractors are adopting group bidding decision-making to reduce the number of incorrect decisions. However, previous related studies mainly focus on project factors that overlook the members of bidding groups and the interaction between bidding group members. The aim of this paper, therefore, is to investigate the potential factors that influence group bidding decision-making for construction projects. Twenty factors relating to individual, group, and organizational levels are identified through a literature review and interviews with experienced practitioners. A questionnaire survey of 203 Chinese international contractors is conducted to obtain the importance of the factors involved. The results of the ranking analysis indicate 14 critical factors, among which “risk perception” and “team decision preference” are regarded as the two most significant. Moreover, 20 factors can be classified into five groupings: (1) values and strategic goals, (2) collaboration and learning orientation, (3) consensus reaching, (4) risk awareness, and (5) empowerment and development, with risk awareness having an especially strong influence. This research deepens the understanding of factors belonging to different organizational levels that need to be highlighted during the group bidding decision-making process and provides strategies for bidding groups and their companies to improve their decision performance.

1. Introduction

The construction industry is a highly uncertain industry [1, 2] where decision-making under risk is common [3, 4]. Of all the risks involved, the decision to bid or not to bid for construction projects is a primary task and critical for project success, as well as a crucial strategic decision affecting contractors’ survival and prosperity in the industry [5].

Bidding decisions and factors influencing the processes involved have elicited wide attention in previous studies relating to construction management (CM) [6–10]. However, the focus of these studies is mainly on project characteristics, the construction companies’ resources available, and economic environmental factors such as market conditions. The studies largely ignore the interactions between individual members in group decision-making concerning available project opportunities, the bid/no bid, and the bid price.

Group bidding decision-making is a process in which group members discuss specific project opportunities in order to make their bid/no bid decisions. Compared to individual bidding decision-making, a group of several individuals with different experiences and expertise are able to communicate with each other to reduce the decision deviation [11, 12]. For that reason, large- and medium-sized construction companies are more likely to adopt the group bidding decision-making in preference to decisions made by individuals.

The group decision-making processes of construction companies are quite diverse [13]. The groups need to establish a hierarchy based on experience, previous performance, persuasiveness, and ability to judge the relative power or knowledge of the individuals involved [14, 15]. In most cases, the international contractors will create the temporary bidding group for a specific project, and this kind of group usually includes a group leader and several technical and business experts that come from different units. Hence, the interaction and communication between group members can have a significant influence on the decision process as well as on the group's final decision. However, most studies where potential factors are explored are in the field of psychology, and these studies generally focus on the specific kinds of influencing factors (e.g., majority and minority influences, group size, and framing) by conducting psychological experiments [16–19]. Few studies have investigated the factors affecting group bidding decision-making systematically, and none has addressed the real world of bidding for construction projects.

For these reasons, this paper aims to investigate the potential factors that influence the group bidding decision-making process for construction projects.

2. Literature Review

2.1. Project Factors for Bidding Decisions. A variety of researchers have paid attention to identifying and analyzing the factors influencing the bid/no bid decision, to provide support for reasoned bidding decisions [8, 20–23]. Early work mainly involved the bidding factors unique to countries and geographical regions, such as Ahmad and Minkarah [24] identified 31 key factors affecting the bidding decision process of contractors in the USA, which provided the foundation for follow-up studies [7]. Shash [25] identified 55 factors characterizing the bidding decision-making of contractors in the UK. However, these studies did not attempt to distinguish between factors.

Some researchers have identified bidding decisions factors and discussed likely taxonomies. For example, Bagies and Fortune [26] built a comprehensive list of bidding factors comprising 10 categories: (1) project characteristics, (2) business benefits, (3) client characteristics, (4) the contract, (5) project finance, (6) percentage of insurance premium, (7) firms' previous experience, (8) the bidding situation, (9) the economic situation, and (10) competition. Egemen and Mohamed [21] developed a hierarchical structure of factors affecting bidding decisions that has three main categories: (1) firm related, (2) project related, and (3) market condition/expectations and strategic considerations related.

Recent work by Jarkas et al. [5] attempts to build the classification criteria that can possibly include and represent almost all these categories for application regardless of geographical region. Moreover, their research was also adopted by subsequent research such as Hwang and Kim [22]. This involves the following:

(1) *Employer-related factors*: previous experience of the contractor with the employer; the employer's financial stability, identity, reputation, strength, position, and special requirements; the employer's promptness in payments process and efficiency in decision-making; and qualifications and quality of the staff.

(2) *Project-related factors*: project type, size, location, safety level, complexity level and equipment type, identity of designer, and construction supervisor.

(3) *Bidding situation-related factors*: tendering method and duration, identity and number of bidders, availability of other projects, the purchasing price of tender documents, and bid bond size and validity.

(4) *Contract-related factors*: contract type, conditions and duration, payment scheme, the quality level of tender documents, value of liquidated damages, size and validity of security bonds, and insurance premium required.

(5) *Contractor-related factors*: availability of required cash, labor and equipment and subcontractors, facilities available to contractors from financial institutions, the quality of available contractors' staff, previous experience and profit in similar projects, current workload, need for work, and need for public exposure.

In addition, some studies focus on analyzing the interrelations between bidding factors or exploring effects of bidding factors on bidding results. For example, Olatunji et al. [23] identify 11 critical factors that influence contractors' bid/no bid decisions and analyze the correlations between these factors. Aznar et al. [6] identify 11 bidding factors and examine effects of these factors on bidding success. Some studies also investigate factors and propose a decision model to aid bidding. For example, El-Mashaleh [8] investigated the factors affecting bidding decisions and then built a bidding decision model using data envelopment analysis (DEA), while Leśniak and Plebankiewicz [9] identify the factors affecting bidding decision-making and then employ fuzzy set theory to develop a bidding decision model.

A shortcoming of previous studies focusing on the factors influencing bidding decision-making has been a failure to consider the influence of the interactions between bidding group members on bidding decision-making. The processes involved in group bidding decision-making are becoming more complex due to the interactions and interdependencies among group members [27]. On the one hand, group decision-making can generate higher quality decisions through communication among team members, but on the other hand, it also suffers from such issues as disagreement among group members due to groupthink [28]. Hence, when the bidding decisions involve a group of decision makers, both the project factors mentioned above and factors affecting the interactive group decision-making process should be thoroughly considered. Considering the limitation of existing studies, this paper identifies and analyzes potential factors affecting the bidding group's decision-making process and provides construction practitioners with a deeper understanding of group bidding decision-making.

2.2. Individual, Group, and Organizational Factors of Group Bidding Decisions. Except group-level factors, the traits of individual members and also the organizational context will shape the group decision-making [27]. Thus, group bidding decision-making is a multilevel phenomenon that must account for individual, group, and organization processes. The factors that belong to different organizational levels influencing group bidding decision-making are identified as follows.

2.2.1. Individuals. Group bidding decision-making is based on individual bidding decision-making, which is a typical kind of risky decision-making that can be viewed as a choice between prospects and gambles [29]. There are two main steps involved when people face decision problems under risk: understanding the problem and making a choice.

Risk perception can generally be defined as the decision-maker's assessment of the risk inherent in a situation [30] and plays a prominent role in the decisions people make [31]. *Risk preference*, on the other hand, describes what one does when faced with a risky option and a safer alternative and is an important predictor of behavior under risk [32, 33]. As Mellers and Cooke [34] point out, no decision model can describe all risk decision behaviors. Moreover, the behaviors may be influenced not only by circumstantial factors but also by risk preferences.

2.2.2. Groups. Organizations frequently require decisions to be made by a group of individuals [35], as the group consensus is expected to provide decisions of a higher quality [36]. In the field of psychology, social decision scheme (SDS) theory [37] is often viewed as the foundation of group decision-making, where the SDS is a rule or procedure that enables decision-making to be made where risk and influential factors are involved.

Much work has been done based on SDS theory to identify influential factors and explore the impact of these factors on the group decision-making. For example, *taking expertise into account* has an important influence on the group's decision, and the group's ability of recognition of expertise of its members is necessary for the group's success [38]. *Majority influence* is also another significant factor [19], where 50 percent or more of the group members reach an agreement in the decision process is said to constitute compliance from these members without the need for detailed processing of their messages [39]. The difference in the *number of group members* also has an effect on the way they come to an agreement [40], while *communication* is the medium for group interaction and can be viewed as constitutive of group decisions [15], with different kinds of communication contributing to different outcomes [41].

2.2.3. Organizations. Unlike individuals and groups, organizations themselves cannot make decisions. Groups always belong to an organization, which means the operations of the group are impacted by organizational context [42]. The dimensions of organizational-level factors include organizational capacity, organizational culture, and organizational structure [43, 44]. These different dimensions of an organization, that is, organizational culture, provide an organization's identity. Organizational culture shapes its members ways of behaviors and decisions [1, 45], and previous research also has demonstrated that it has an significant impact on team decisions [46]. Hence, organizational culture factors are identified as factors belonging to the organizational level that influences group bidding decisions.

A variety of theoretical frameworks of organizational culture have been proposed. Of these, Denison's organizational culture model (DOCM) is well recognized for analyzing organizational culture and has been widely applied in the construction sector [1, 45, 47]. Therefore, DOCM is selected in this research to investigate the factors affecting the interactive group bidding decision-making process at the organizational level. Denison's model has four main cultural characteristics: adaptability, mission, consistency, and involvement [48]. Firstly, "adaptability" considers an organization's ability to perceive and respond to the environment and comprises *creating change*, *customer focus*, and *organizational learning*. Secondly, "mission" considers the extent to which organizations have a mission that informs employees why they are doing the work they do and how the work they do each day contributes to why they are doing it. This contains *strategic direction and intent*, *goals and objectives*, and *vision*. Thirdly, "consistency" provides a central source of integration, coordination, and control and helps organizations develop a set of systems that create an internal system of governance based on consensual support. This consists of *core values*, *agreement*, *coordination*, and *integration*. Fourthly, "involvement" is concerned with creating a sense of ownership and responsibility in order to develop greater commitment to the organization and an increased capacity for autonomy. This is composed of *empowerment*, *team orientation*, and *capability development* [49].

3. Research Methodology

The research used literature review, in-depth interviews, and a questionnaire survey for data collection. The first step was to identify the preliminary factors influencing group bidding decisions through a thorough literature review and comprises two stages. In stage 1, the research searched for articles relating to factors belonging to the individual, group, or organizational level that influence bidding decision-making in the CM field. In stage 2, articles were selected relating to factors influencing group decision-making but not limited solely to group bidding decision-making. During this stage, we not only searched group decision-making factors in articles in the CM field but also considered related articles in the fields of general management and psychology. After the search process, 18 factors belonging to individual, group, and organizational levels were identified from the final selected articles.

In the second step of the research, in-depth face-to-face interviews were conducted with 32 middle and senior managers of Chinese international contractors to test the feasibility and comprehensiveness of the factors identified in the first step. Each interviewee's company used group bidding decision-making, and each interviewee had experience of the decision-making processes involved. The interviewees were asked to comment on whether the provisional factors listed covered all possible factors, considering the context of Chinese contractors venturing into overseas markets, whether any factors could be added, deleted, or modified. This resulted in the confirmation of the influence of the identified factors and provided suggestions for two other potential factors of "personal interest" (individual) and "team decision preference" (group). The final set of factors is summarized in Table 1.

A questionnaire survey was conducted in the third step to obtain the importance of identified factors and facilitate subsequent analysis. The target population was experienced

Table 1: Factors identified from the literature review and interviews.

Number	Factors	Description	Sources	Levels
1	Risk perception	The group member with higher risk perception would more likely to bid low-risk projects	[50]	Individual
2	Risk preference	The group member who is more risk seeking would more likely to bid high-risk projects	[51, 52]	
3	Personal interest	Most of the group members prefer to make a bid decision that could meet their personal interest (e.g., profits and future development)	Interview	
4	Number of group members	The size of bidding group will affect the time of reaching consensus, and it also plays a role in the decision quality	[16, 53]	Group
5	Majority influence	A majority of group members often hold the power and impose their opinions on the minority during the decision-making process	[19, 39]	
6	Taking expertise into account	The group's ability of identification and utilizing of expertise of its members is vital to the decision-making performance	[38]	
7	Communication	The efficient communication among group members will promote the information flow and improve the decision quality	[27, 54]	
8	Team decision preference	The group's preference determined by previous bidding experiences will impact its bidding decisions in the future	Interview	
9	Organizational learning	Learning orientation decreases the possibility of making wrong bidding decisions in the future	[1, 55]	Organizational
10	Customer focus	The degree of willingness of serving clients' needs has an effect on the group's biding decisions	[49]	
11	Creating change	The ability of adopting improved and new ways in the work impacts the group's bidding decisions	[1, 45]	
12	Core values	Internalized values guide organization members' behaviors and thus influence the group's bidding decisions	[1, 56]	
13	Agreement	The ability to reach agreement on difficult issues is critical to the group bidding decision performance	[28, 57]	
14	Coordination and integration	The degree of group members from different units working together for a common goal significantly influences the decision-making process	[1, 58]	
15	Vision	A clear view on the state in the future will encourage group members to take risk during the bidding decision	[1, 59]	
16	Goals and objectives	If clear goals are provided for group members, then the bidding group is more likely to make reasonable decisions	[1, 60, 61]	
17	Strategic direction and intent	A clear view on long-team purpose and direction prevents group members to underestimate real risks of the current project	[1, 62]	
18	Empowerment	Group members which come from an empowered organization are willing to share their knowledge during the decision-making process	[63, 64]	
19	Team orientation	The degree of the organization emphasizing the importance of teamwork influences bidding groups' cohesion and decision performance	[1, 45]	
20	Capability development	The degree of the organization emphasizing the investigation of employee development influences bidding group members' competitions and decision performances	[1]	

construction industry personnel who had attended group bidding decision-making or carried out bidding preparation work and who were familiar with the bidding process of their respective firms and departments.

A pilot study was carried out with 10 middle or senior managers from different enterprises to check the relevance of the questions and to identify any ambiguities in the wording of the questions. Based on their suggestions, the

Table 2: Profile of respondents.

Characteristics	Categorization	Number	%
Working experience	Below 5 years	44	21.7
	5–10 years	62	30.5
	11–15 years	49	24.2
	16–20 years	35	17.2
	Over 20 years	13	6.4
Title	Senior manager	29	14.3
	Department manager	58	28.6
	Project manager	116	57.1
Working location	Asia	102	50.2
	Africa	43	21.2
	Europe	21	10.3
	North America	10	5.0
	Latin America	27	13.3

questionnaire was revised to improve its precision and readability. In the final questionnaire, a 5-point Likert scale was used to measure respondents' views concerning the influence of the factors (1 = very low influence, 3 = moderate influence, and 5 = very high influence).

Due to the difficulty in developing a sampling frame, the nonprobability sampling technique was adopted, which is considered appropriate when respondents are selected based on their willingness to participate in the survey rather than random selection [65]. The specific sampling approach employed in this research is the snowball sampling method (i.e., respondent-driven sampling), in which respondents share or know others who also had experiences of group bidding decision processes involved. Estimates generated from the data of the snowball sampling method are asymptotically unbiased, no matter how the seeds are chosen [66–68]. Based on this method, a list of 264 potential respondents was developed. We connected respondents in the list to further verify that they have related knowledge of group bidding decisions and invite them to participate in this survey. Then, each respondent was sent the questionnaire, and a total of 216 responses were received. After strict screening, 13 improperly completed returns were removed, resulting in 203 responses finally used for data analysis. The profiles of the respondents are shown in Table 2.

4. Data Analysis and Results

4.1. Ranking of Factors. Cronbach's alpha coefficient is 0.896, which is much higher than the threshold of 0.70 [69], indicating high data reliability. As indicated in Table 3, the mean scores of 20 factors range from 2.807 to 4.145. To select the critical factors, the normalized values of mean scores are calculated. The same method was applied by Xu et al. [70] and Zhao et al. [2], who determined critical factors to be those with normalized values equal to or greater than 0.50. Applying this principle here, the factors with mean scores closer to the maximum mean of all factors are regarded as critical factors. 14 of the 20 factors have normalized values greater than 0.50 and are therefore deemed critical (Table 3).

Of these, "risk perception" is ranked first, which indicates that each individual group member is aware of, and has an opinion about, the possible risks in each case. "Team decision preference" is ranked second, indicating that nearly all the respondents' companies have their own decision tradition that they will follow without question. In the interviews, some interviewees pointed out that their group members generally do not bid in some circumstances.

"Organizational learning" is ranked last. Thus, this factor is less important, which is confirmed by the general comments during the interviews. The main reason to this result may be that the preferred project type and location are relatively steady, and that little attention is paid to increase capabilities to adapt to external change. An explanation for the second last factor, "personal interest," can also be found in the interviews, where a manager explained that all companies have to consider the personal interests of their staff by rewarding them in one way or another when the company makes a profit. In other words, there are few situations where there is a conflict between the company interests and staff personal interests.

4.2. Exploratory Factor Analysis. Exploratory factor analysis (EFA) can identify a relative small set of underlying factors' groupings that can be used to analyze correlations among a large set of interdependent variables. Therefore, this method is applied to explore the underlying groupings among the 20 identified factors involved.

The ratio of the sample size to the number of factors is 10.15, which is higher than the ratio of 5.00 recommended by Gorsuch [71]. This indicates that the sample size is significantly large enough for EFA. The factorability of the item correlation matrix is tested by using the Kaiser–Meyer–Olkin (KMO) index (KMO $\geq$ 0.50) and the Bartlett test of sphericity. The KMO value is 0.826, indicating a high degree of common variance among factors. The Bartlett test of sphericity result is 412.003, with 0.000 significance, indicating that the population correlation matrix is not an identity matrix. Hence, the data are appropriate for EFA. Principal component analysis is adopted to identify the underlying factor groupings, resulting in the extraction of five groupings with eigenvalues greater than 1. The five factor groups explain 80.59% of the variance (as indicated in Table 4), higher than the guideline of 60% recommended by Malhotra [72]. Table 5 presents the groupings based on varimax rotation. The factor loading value represents the contribution of individual factors to each underlying grouping, and all factor loading values exceed the 0.45 value recommended by Comrey [73].

4.2.1. Values and Strategic Goals. The "values and strategic goals" grouping comprises five factors: (1) vision, (2) goals and objectives, (3) strategic direction and intent, (4) team orientation, and (5) core values.

This grouping reflects the influences of consistent values and clearly defined strategic objectives of the company for the bidding group's decision-making process. Values of companies are reflected in various aspects (e.g., business ethics, relationships, and strategies) [1], and these values govern how the group members work. For example, if the

Table 3: Ranking of the factors.

Number	Factors	Mean value	Rank	Normalization[a]
1	Risk perception	4.145	1	1.00
2	Risk preference	3.828	4	0.76
3	Personal interest	2.981	19	0.13
4	Number of group members	3.577	11	0.58
5	Majority influence	3.803	5	0.74
6	Taking expertise into account	3.114	17	0.23
7	Communication	3.792	7	0.74
8	Team decision preference	4.038	2	0.92
9	Organizational learning	2.807	20	0.00
10	Customer focus	3.532	13	0.54
11	Creating change	3.097	18	0.22
12	Core values	3.761	9	0.71
13	Agreement	3.801	6	0.74
14	Coordination and integration	3.254	16	0.33
15	Vision	3.434	15	0.47
16	Goals and objectives	3.512	14	0.53
17	Strategic direction and intent.	3.725	10	0.69
18	Empowerment	3.899	3	0.82
19	Team orientation	3.787	8	0.73
20	Capability development	3.561	12	0.56

[a]Normalized value = (mean – minimum mean)/(maximum mean – minimum mean).

Table 4: Total variance explained for factors.

Groupings	Initial eigenvalues		
	Total	% of variance	Cumulative %
1	5.398	26.991	26.991
2	4.021	20.105	47.096
3	3.022	15.112	62.208
4	2.074	10.371	72.579
5	1.602	8.009	80.588

Table 5: Grouping matrix after varimax rotation.

Number	Factors	Grouping				
		I	II	III	IV	V
15	Vision	0.912	—	—	—	—
16	Goals and objectives	0.874	—	—	—	—
17	Strategic direction and intent	0.831	—	—	—	—
19	Team orientation	0.695	—	—	—	—
12	Core values	0.542	—	—	—	—
13	Agreement	—	0.811	—	—	—
7	Communication	—	0.734	—	—	—
14	Coordination and integration	—	0.605	—	—	—
9	Organizational learning	—	0.501	—	—	—
5	Majority influence	—	—	0.837	—	—
4	Number of group members	—	—	0.749	—	—
6	Taking expertise into account	—	—	0.595	—	—
10	Customer focus	—	—	0.577	—	—
1	Risk preference	—	—	—	0.832	—
2	Risk perception	—	—	—	0.797	—
8	Team decision preference	—	—	—	0.642	—
18	Empowerment	—	—	—	—	0.697
20	Capability development	—	—	—	—	0.665
11	Creating change	—	—	—	—	0.628
3	Personal interest	—	—	—	—	0.610

Notes. Grouping names: I: values and strategic goals; II: collaboration and learning orientation; III: consensus reaching; IV: risk awareness; V: empowerment and development.

companies' strategic value is to maintain a good reputation in the industry, then group members would conduct an adequate evaluation of the probability of executing a project successfully before deciding to bid for it instead of just calculating the potential profit their company would receive. If the companies' values are to trust and respect each other in their relationships, then the group members' relationships will be closed and the group will be cohesive during its work. The company's strategic goals are an important trait that determines the bidding group's risk-taking behavior, and the group's bidding decision needs to coincide these. In particular, the Chinese government's recent "One Belt One Road" (OBOR) initiative has a primary aim of improving the connectivity between countries along the OBOR trade corridors. This initiative will create huge opportunities for international construction companies. In this context, the interviews revealed that most of Chinese construction companies' strategic goals include actively taking part in this initiative and developing markets in countries along the route. This goal will encourage the bidding group to take risks in such decisions.

4.2.2. Collaboration and Learning Orientation. The "collaboration and learning orientation" grouping contains four factors: (1) agreement, (2) communication, (3) coordination and integration, and (4) organizational learning.

This group reflects the important role of cooperation and sharing thoughts between group members in improving the quality of the group's bidding decisions. It also reflects the importance of the learning process when making decisions in highly uncertain conditions. The key element differentiating group decision-making from individual decision-making is information exchange between group members [54, 74]. In most cases, the construction company will create a temporary bidding group for a specific project. The members of this kind of group are usually from different units, which may have different working habits. Hence, guaranteeing effective information exchange between the members in these temporary groups is vital for achieving high decision performance. A company emphasizing collaboration can build an open atmosphere for communication and promote resource sharing between group members from different backgrounds. The interviews indicate that most of the senior managers of

Chinese international contractors value this and point out that there will be no success unless everyone shares information. Learning orientation reflects the degree to which an organization values using and creating knowledge to survive and develop. A learning climate in a construction company will encourage the bidding group to absorb previous mistakes. Moreover, a company highlighting learning will also create an effective information sharing system, which enables the group to eventually reach better decisions.

4.2.3. Consensus Reaching. The "consensus reaching" grouping comprises (1) majority influence, (2) number of group members, (3) taking expertise into account, and (4) customer focus.

This grouping is mainly linked to the group level, and factors such as majority influence, number of group members, and taking expertise into account represent fundamental features of group decision-making. The group with large size is more likely to produce high performance [16]. However, the performance of the group will also decrease if the group size increases continually [75], because extremely large group size increases the probability of generating disagreements and the time to reach a consensus. A powerful majority is also significant in driving the consensus of the group. Bidding groups also need to pay attention to minority opinions, since they can provide multiple perspectives and alternative plans. A bidding group needs to focus on the efficiency of decision-making (e.g., decrease the time to reach a consensus) while guaranteeing higher quality decisions. Therefore, during the bidding group design phase, company managers and group leaders should guarantee that the group will include adequate members to accomplish group goals and avoid the group size being overly large at the same time. In addition, the application of appropriate decision rules is also necessary during the group bidding decision process.

4.2.4. Risk Awareness. The fourth grouping encompasses the following factors: (1) risk preference, (2) risk perception, and (3) team decision preference.

This grouping reflects the individual as well as the group process when making a decision under risk. It is noteworthy that all three factors in this grouping are ranked among the top four influencing factors, indicating it plays a key role in the process of group bidding decisions. In the interviews, although the interviewees emphasized the importance of discussion, cooperation, and compromise, the results clearly show that the foundation of all these is the essence of bidding is a decision-making issue under risk. Before discussion, cooperation, and compromise, everyone participating in these procedures needs to have their own judgment of the problem based on "risk awareness." "Risk awareness" has an invisible influence on decision-making, which is worthy of consideration. If the risk awareness of all decision makers is similar, it is easy to make a decision. However, the opposite is the case if the decision makers have big risk awareness differences. Therefore, it can be concluded that the team should have broad perspectives on risk and agreement on the risk decision.

4.2.5. Empowerment and Development. The factors belonging to this grouping are (1) empowerment, (2) capability development, (3) creating change, and (4) personal interest.

This grouping reflects the importance of the construction companies' efforts in empowerment and investing employee development in guaranteeing a high group bidding decision quality and is linked to both organizational and individual levels. Although the bidding group's final decision needs be audited and approved by top managers in most construction companies, many interviewees agreed that whether the company bid for a project is largely determined by the bidding group, since their companies are quite trusting the group and rarely deny the bidding scheme. The prosperity of construction companies' is significantly affected by the bidding group's quality of work, which relies on each members' active participation in the process. A company that emphasizes empowerment and investing in employee development will create a shared perception that their company pays attention to their future development and views them as important resources for competitive advantage, which will improve their sense of belonging to the company and responsibility in their work. Hence, a construction company that values these traits will encourage group members to find new ways to solve problems, increase their confidence to accomplish work tasks, and indirectly improve the group's quality of work.

Initially, therefore, the factors were identified from three-organizational levels (individual, group, and organization) and, after a relationship analysis, they were categorized into five channels. The correlation between the initial categorization and the new categorization is shown in Figure 1.

5. Conclusions and Recommendations

This study identifies and analyzes the factors that influence group bidding decision-making for construction projects. The analysis results indicate that 14 out of the 20 factors relating to individual, group, and organizational levels were identified to be critical factors, of which "risk perception" and "team decision preference" are regarded as the two most significant. In addition, the factors can be assigned into five groupings: (1) values and strategic goals, (2) collaboration and learning orientation, (3) consensus reaching, (4) risk awareness, and (5) empowerment and development. Influence of the grouping risk awareness is especially strong among the five groupings, with all three factors belonging to this grouping being ranked among the top four influences on decision-making.

The managerial implications that can be drawn from this research are as follows:

(1) Bidding groups act in an organizational context and the construction companies need to set an appropriate strategic goal and ensure that employees at all levels have a clear understanding about this goal to provide direction for bidding groups' decision-making.

(2) Except for emphasizing material incentives, construction companies are also encouraged to invest in developing their organizational culture, and traits

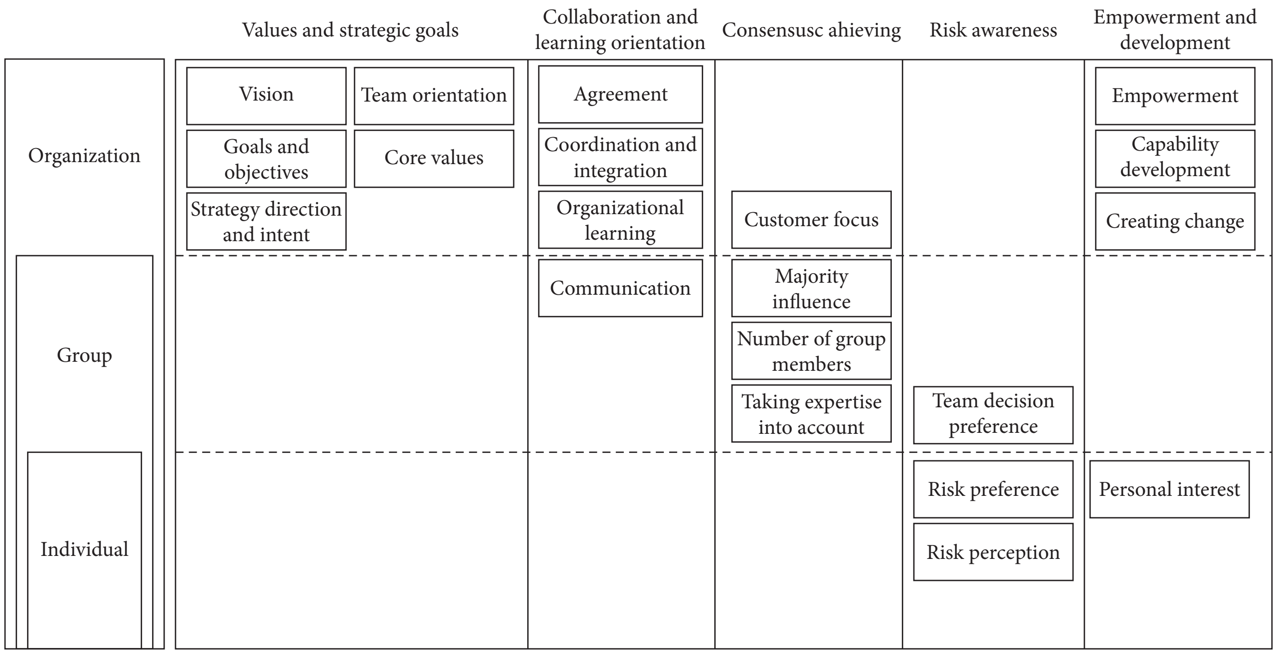

Figure 1: The system of factors on three-organizational levels influencing group decision-making.

such as collaboration and empowerment are vital for increasing the bidding group's cohesion and the responsibility of group members.

(3) The bidding group should be aware of the risk perceptions and risk preferences of group members and consider their risk characteristics during the decision-making process.

(4) An appropriate group size and provision of effective decision rules is helpful for the bidding group to achieve a consensus from different points of views during group discussions, and a deep understanding of each group member's expertise is also advisable.

Moreover, besides bidding groups formed by members from different units of a company, groups including members from different companies are also common in current large-sized projects due to increasing adoptions of construction joint ventures (CJVs) agreements. The factors identified in this research are not limited to the specific group type. Therefore, it can be believed that the findings of this research can provide wide implications for both the single company and CJVs to improve their group bidding decision performance.

Although the study sought out the potential factors influencing group bidding decision-making, there are some limitations and future associated research opportunities. First, this research focused on analyzing the factors belonging to different organizational levels that influence group bidding decision-making in construction projects, while ignoring such others as project factors, market factors, and government-related factors. Further research is needed to investigate the factors that affect group bidding decisions from a more comprehensive perspective. Moreover, the data were collected mainly from the Chinese overseas contractors, and further research could also be carried out using similar methods in detailed comparative studies between the different enterprises in different countries. The relationships between the five groupings classified in this research are also worthy of further study.

Data Availability

The data used to support the findings of this research are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

Estimating the Influence of Improper Workplace Environment on Human Error: Posterior Predictive Analysis

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A model for identifying, analyzing, and quantifying the mechanisms for the influence of improper workplace environment on human error in elevator installation is proposed in this study. By combining a modification of a human error model with real-world inspection data collected by an elevator installation company, the influence paths of improper workplace environment on the conditional probability of human error were quantified using a Bayesian network parameter-learning estimation method and posterior predictive simulation. Under the condition of an improper workplace environment, the probability of human error increased by 80% of its original value, a factor much higher than that resulting from improper management. The most probable influence was found to be improper workmanship and changes in the information required by the worker, thus triggering cognitive failure and consequent unsafe actions by workers. The proposed methodology (posterior predictive simulation) provides a new approach in construction studies for quantifying the probabilistic levels of various causal paths, and the results show the key mechanism for the influence of improper workplace environment on human error using real-world mechanical installation data.

1. Introduction

1.1. Importance of Workplace Environment in Effective Elimination of Human Error. From theoretical and empirical studies [1, 2], human error by workers was found to be the most important causal factor in accidents. If human error in the construction industry can be effectively reduced, the occurrences of construction accidents can be minimized [3, 4]. Previous studies revealed that if the factors of facilities, work methods and operations, processes, equipment, tools, products, new technologies, and work organization that lead to human error in the work environment can be eliminated by an effective workplace environment, the probability of human error can be greatly reduced, and the occurrence of accidents can be controlled [5, 6]. "Workplace environment" ordinarily refers to the environment of workplace in a location during the construction itself, that is, structural and product workplace environments. However, with the gradual integration of workplace environments with construction processes, the workplace environment stage needs to be more connected to the construction stage. Thus, the setup of construction methods and processes must also be included in the general category of workplace environment [7]. Therefore, in the present study, the term "workplace environment" includes both the engineering and process workplace environments. Since theoretical and empirical studies of cybernetics have indicated that a safety-oriented workplace environment is one of the most economic and effective means for controlling accidents [8, 9], experienced workers may still resort to unsafe behavior in response to the work environment conditions and the process demands even under conditions in which unsafe behavior is strictly prohibited [2, 10], thus highlighting the importance of the workplace environment in the elimination of human error.

1.2. Lack of Clarity in Current Understanding of Workplace Environment-Human Error Relationship. Although the importance of an effective workplace environment for the minimization of human error has been confirmed in many studies, existing research does not provide sufficient explanation for the mechanism of the influence of workplace environment on human behavior. This lack is reflected in the following three aspects:

(1) The mechanisms of the influence of workplace environment on human error are asserted on the basis of qualitative (or even scant) explanations, whereas an analytical approach is required to reveal the relative importance of the mechanisms of influence for use as a management reference. Most existing research simply uses statistical correlation as a basis for connecting a structural and/or engineering workplace environment with unsafe behavior. Therefore, the explanation for the mechanism is inadequate. Studies based on workplace environment principles [11], expert opinions [12], or statistical correlation [13] have shown that the probability of occurrence of unsafe worker behavior can be reduced by improvements in the workplace environment [14]. For a type of accident that may occur on a steel structure construction site, Leu and Chang [15] conducted a Bayesian modeling study based on expert opinions and forecasted the probability of various types of accidents by comparisons with actual accident data. Their model covers a wide range of variables, including variables relevant to workplace environment and unsafe human behavior. However, their study focused only on the forecasting of accident probabilities without examining the influence of the variables of workplace environment and human error. In Haslam et al.'s [16] deviation model, the accident path begins with origination influences, is then adjusted by shaping factors, and finally forms the immediate accident circumstances. Though the factors causing accidents were properly abstracted and clustered into groups, the influence of each factor was not quantified. The influence of a factor is shown intuitively by the proportion of accidents in which that factor is involved, which ignores interactions between factors and provides no confidence level for the measurement. Furthermore, these studies do not provide an analytical approach that demonstrates the relative importance of the mechanics of influence for use in the allocation of management resources.

(2) Most data have been collected from questionnaires, expert decisions, and other subjective methods [17–19]. Compared with actual engineering data, this data collection process and use of subjective data are more likely to cause random error and deviation, leading to inaccurate results. Li et al. [20] stated that the lack of an accurate and comprehensive database is the main difficulty in the study of human error. In their study, the fuzzy Bayesian method was introduced to deal with a variable value, but still the basic data were the scores given by experts who estimated the conditional probability for each causal relationship, affecting the reliability of the results. In the study by Leu and Chang [15], actual accident data were used to verify the reliability of the model. However, the accident causation model was still heavily expert-driven, and deviation in the result caused by the subjective data was not eliminated.

(3) Although modeling research studies have been conducted to address the relationship between workplace environment and human error, the existing theoretical models and methods require the incorporation of the psychological states of workers who interact with the work environment in order to discover the drivers of human errors. Jiang et al. [21] assumed that behavior is the product of human cognition on the environment, that is, that the most direct cause of human error is cognitive failure, where cognitive failure depends on individual factors (including physical and psychological conditions) and environmental factors (risk exposure). However, they did not explain how the environment imposes constraints that cause cognitive failure and further result in human error.

As can be seen from the gaps summarized above, the existing research results are not able to clearly explaining the mechanism for the influence of workplace environment on the occurrence of human error. Thus, individual project participants do not have a sound basis for evaluating the importance of a safe workplace environment, and workplace designers and owners lack impetus and motivation to participate in and implement safety programs for the workplace environment, which are the major challenges in promoting error prevention through the workplace environment. By clearly identifying the mechanism of influence between the engineering workplace environment and human error in the construction industry, the concept of error prevention through the workplace environment can be further promoted. Therefore, on the basis of the models proposed by the aforementioned research, the present study uses real-world observation data to analyze and explain the mechanism for the influence of workplace environment on human error.

1.3. Challenges of Human Reliability Analysis in the Construction Industry. Because the construction industry needs a mechanistic model for workplace environments that address unsafe human behavior, an important tool is the human reliability analysis (HRA), which analyzes the probability of success of those activities that must be accomplished in terms of the reliability or availability of the system [22]. However, the HRA method is more often used in industries such as nuclear energy, aviation, and related fields [23–25]. In contrast to these fields, the operation site of a construction project features lower automation, greater personnel mobility, more rapid changes in the construction environment, and more open systems (vulnerable to external factors such as weather) [26]. Therefore, using the HRA method to analyze problems in the construction industry is a great challenge [27]. For example, compared with the construction industry, the nuclear power industry is highly automated, with more machinery and system operations that are carried out by workers. Thus, the cognitive reliability and error analysis method (CREAM) designed for the nuclear power industry has relatively more descriptive variables [28]. In addition, these factors are not dominant in a construction project. In a construction project, the work environment faced by workers is relatively complicated and varied, which is not well captured by the HRA method [29, 30]. As a result, the probability of human error (HEP) cannot be accurately calculated in order to measure the influence of workplace environment on human error. Therefore, in order to apply the HRA method to a construction project, the variables and their definitions need to be modified to suit the characteristics of a construction project.

Although the CREAM incorporates psychological factors (e.g., inattention and missing observations) in the mechanisms of influence between the workplace environment and human errors, studies show that the application of HRA in various industries also shares common defects [31, 32] as follows:

(1) *Lack of available data*: For HRA, the most serious problem is that the data sources are too broad to be applied to specific industries [33]. Thus, if a particular industry wants to understand its specific problems, it must collect data from scratch [34].

(2) *Over-reliance on expert judgment*: In the existing HRA method, the evaluation of factors that influence human errors (performance-shaping factors (PSFs)) and the probability of occurrence rely mainly on the subjective judgment of experts, which can easily cause a large random error [20, 31, 35, 36].

(3) *Coarse measurement of variables having no clear boundaries*: Although methods such as the existing CREAM backtracking can provide the relationships between different PSFs and most HRA methods that have descriptions for different error types, their level of description is too coarse and there are no detailed assessment indicators. This raises doubts about the accuracy of the HEP values calculated by these methods.

Despite these gaps, Liao et al. [37] had proposed a human error model based on the CREAM that includes more variables that capture the characteristics of construction projects. The mechanisms by which improper workplace environments can cause human error in construction can only be identified when the existing variables and their definitions are further modified according to the characteristics of the construction project and when its data are used as the basis for parameter estimation. Although the influence paths for improper workplace environment and human error were identified, the topology of the model requires revisions based on industrial experience to make the model suitable for parameter estimation, and the results need to be mapped and validated with previous studies to corroborate the legitimacy of the results. This study proposes an analytical approach, posterior predictive simulation, based on real-world observations, to answer the following questions: (1) In terms of conditional probability, how much does improper workplace environment contribute to the rate of occurrence of human error? (2) How can the mechanisms of influence be ranked according to the quantity of human errors resulting from an improper workplace environment?

2. Methodology

The goal of this study was to demonstrate an approach to discover and prioritize the impact of improper workplace environment on the probability of occurrence of human errors. First, an influence model (a Bayesian network) published in a previous study was modified, and then, real data were mapped onto the influence model. Second, parameter estimation was performed using the expectation-maximization algorithm to estimate the levels of influence for improper workplace environment on the probability of occurrence of human errors. Third, by comparisons with the baseline derived from posterior predictive simulation, the influence levels of various paths were quantified. Lastly, the focus was turned to discussions of various paths by which an improper workplace environment can lead to human errors, and the results were compared with those of other studies for validation purposes. Details of the methodology and of its implementation for this study are presented in the sections that follow.

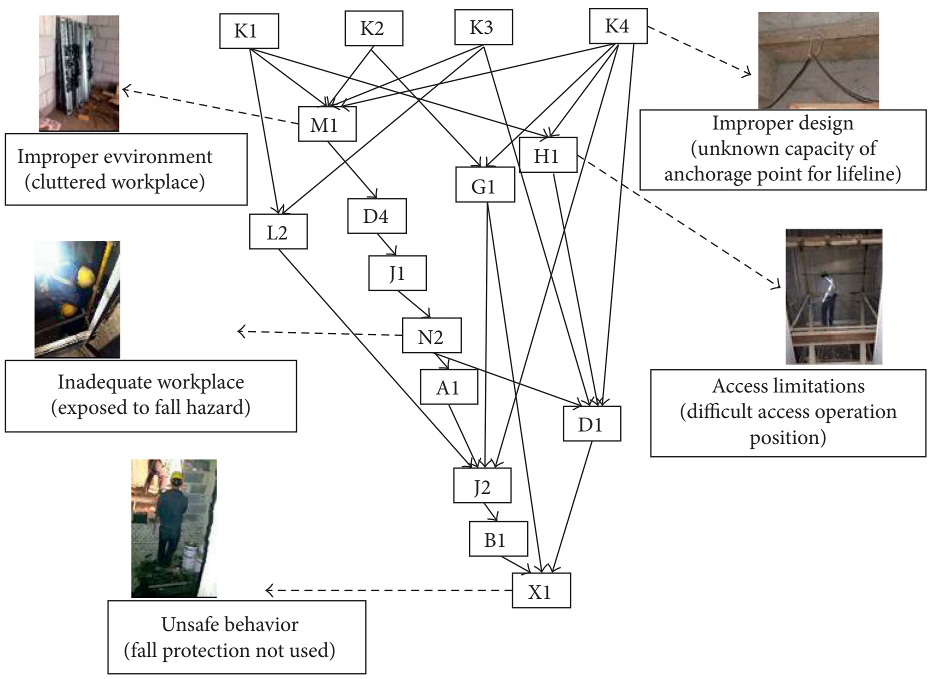
2.1. Modification of the Influence Model: Bayesian Network. First, this study adopted a focused group discussion adaptation of the model proposed by Liao et al. [37] using negative proposition logic. The principle was as follows: as long as two or more members in the focused group raised questions in the model, these questions would be discussed and modified until all members reached an agreement or only one of all members did not support the model, i.e., if the focused group proposed that a certain causal link did not exist or there was not only one variable in the influence path, then the chain of causality would be removed or other possible variables would be considered. The modified Bayesian network (BN) model is shown with the names of the nodes (each of which corresponds to a risk factor, such as faulty diagnosis or inadequate procedure) in Figure 1.

Second, the safety-inspection records collected by an international mechanical installation company were mapped to the model variables according to the following rules:

(1) Is the description of the observational variable a potential danger to the workers themselves? If so, it is deemed to belong to the category of human error. If it only creates an unsafe environment or unsafe condition, then it is identified as one of the PSFs.

(2) By comparing the descriptions of the observational variables with the company safety regulations, the specific object with an error or the environment state is categorized to match the model variables.

For example, a certain observational variable (risk), namely, workers having no protection against falling while working on a ladder at elevations higher than 2 m, would be described by the safety rule as “workers must be protected against falling when working at elevations higher



Node	Content
A1	Observation miss
B1	Faulty diagnosis
D1	Memory failure
D4	Inattention
G1	Inadequate procedure
H1	Access limitations
J1	Communication failure
J2	Missing information
K1	Insufficient maintenance
K2	Inadequate quality control
K3	Improper management
K4	Improper design
L2	Insufficient knowledge
M1	Improper environment
N2	Inadequate workplace
X1	Wrong sequence (unsafe behavior)

Figure 1: Human error model for construction industry using an elevator installation as an example.

than 2 m." This rule focuses on whether fall protection is used while working, which belongs to the description of human behavior. By comparison, this example is found to be consistent with the definition of the model variable "wrong sequence"; that is, one or more operations in an action sequence were skipped. Therefore, this risk item is mapped to this model variable. For instance, the node "wrong sequence" was mapped with the predefined human error "fall protection not used when exposed to a fall hazard."

The expectation-maximization (EM) algorithm was used to estimate the various variables in the model and obtain the conditional probability table (CPT) for each variable. In addition, a posterior predictive simulation was used to set all the root nodes in the network to either zero or one, and the conditional probability of the corresponding unsafe human behavior was calculated according to the CPT. By comparison, the influence of each root node on unsafe human behavior was obtained, and an understanding was gained of the potential influence of the workplace environment on the probability of occurrence of human error that is due to a number of factors.

Finally, the most probable path from workplace environment to human error was selected. The numerical value for the influence of each path was calculated by evaluating the nodes in the path via discussion and identification of the most likely mechanism for the influence of workplace environment on human error.

2.2. Parameter Estimation

2.2.1. Parameter Estimation Approach. Bayesian parameter estimation is a data-learning method that is based on a given BN structure and uses the data to learn the probability distributions of parameters in the networks and nodes. When BN is used to analyze human error, the conditional probability distribution (table) that describes the relationships among nodes can be obtained by parameter estimation. The probability forecasting the final node, that is, unsafe human behavior, can also be studied using the results. By using BN, studies have improved the HRA model by cross adoption of data and expert opinion to increase the credibility of the model. However, because of the high specialization and difficulty of data acquisition in the construction industry, prediction of HEP still relies on the evaluation of experts, which results in low accuracy. Zhou et al. [38] pointed out that the results are often inaccurate when the BN parameter learning only uses pure data calculation, and the method of using expert opinion scores as node probabilities is also inaccurate. With regard to this problem, the combination of expert opinion and data in the parameter learning process is widely believed to effectively improve the accuracy of the probability estimation [39]. Zhou et al. [38] proposed that experts often have difficulty in providing an accurate probability of occurrence of a node but can easily provide a qualitative description. Thus, the reliability of the model could be greatly improved if this type of description can be integrated into it.

BN parameter learning can perform a complete data parameter estimation as well as calculations with missing data. Because the present study performs calculations using actual engineering data, which commonly have missing values, this advantage of BN parameter learning can guarantee the generation of a utilization ratio and thus is very suitable for use as the calculation method in this study. In addition, because BN was previously developed with a relatively mature algorithm, many types of software that can directly perform the estimation process for the Bayesian parameters are now available. In the present study, the Bayes Net Toolbox (BNT) software for MATLAB 2013a was chosen for the BN parameter learning [40].

2.2.2. Parameter Estimation Logic. This study used actual engineering data for the calculation. Because of the high frequency of missing data values, the typical expectation-maximization algorithm, which uses the Bayesian parameter estimation to deal with the missing data, was adopted. The "expectation" step uses the modified maximum likelihood estimation (MMLE) method to estimate the parameters for the missing data nodes; it then uses these estimated values as the data to fill in the missing values [41]. The "maximization" step estimates the parameters. The specific calculation principles are as follows:

(1) *Step E (expectation)*: For missing data point z, the equation of estimation for its MMLE, $l(\theta)$ is expressed as

$$l(\theta) = \sum_{i=1}^{m} \log\, p\left(x^{(i)},\ \theta\right), \tag{1}$$

where θ is the parameter of the MMLE equation, m is the number of data samples, and $x^{(i)}\,(i = 1, 2, \ldots, m)$ is the sample value. For $z^{(i)}\,(i = 1, 2, \ldots, m)$, if Q_i is the probability density function of $z^{(i)}$, then the equation for the original θ and estimate $l(\theta)$ is expressed as

$$Q_i\left(z^{(i)}\right) = p\left(z^{(i)} \middle| x^{(i)}; \theta\right), \tag{2}$$

where $Q_i\,(z^{(i)})$ is the largest estimation point for $l(\theta)$.

(2) *Step M (maximization)*: θ' is the updated parameter of the MMLE, expressed as

$$\theta' = \arg\max \sum_{i} \sum_{z^{(i)}} Q_i\left(z^{(i)}\right) \log \frac{p\left(x^{(i)},\ z^{(i)}; \theta\right)}{Q_i\left(z^{(i)}\right)}. \tag{3}$$

Step M calculates the MMLE of the parameter under the Step E hypothesis. The EM algorithm is a process of iterating Steps E and M. As $l(\theta)$ progressively increases, the estimation process ends when the difference between $l(\theta)$ and $l(\theta')$ decreases to a certain range and remains unchanged.

2.3. Quantification of Influence Levels by Path: Posterior Predictive Simulation. Making predictions with Bayesian methods is trivial. To begin, to estimate unknown parameter θ values given observable outcome y and predictors x, the Bayes rule is used:

$$p(\theta|y,\ x) \propto p(\theta)p(y|x,\ \theta). \tag{4}$$

In this study, a Bayesian network model was used to estimate these unknown parameters. Once the θ values are estimated, an unknown observable $\tilde{y}$ can be created or predicted from the same process (model), conditioning on the observed y, x, and θ. Thus, the posterior predictive distribution of $\tilde{y}$ can be estimated:

$$p((\tilde{y})|y,\ x,\ \theta) = \int p(\tilde{y}|\theta,\ y,\ x)p(\theta|y,\ x)d\theta. \tag{5}$$

Following that, the predictive probability differences (x values) of the various unsafe human behaviors, $\Pr(\Delta\tilde{y})$, can be obtained by changing the x values, and since these are all binary, the following is obtained:

$$\Pr(\Delta\tilde{y}) = p(\tilde{y}'|y,\ x = 1,\ \theta) - p(\tilde{y}''|y,\ x = 0,\ \theta). \tag{6}$$

2.4. Implementation Details. This study used Python programming to screen and preprocess the data and employed the BNT toolbox in MATLAB as the computation software. The model variable system and network structure were input into the software in the form of a matrix recorded in Excel, and the process was set up to loop 20 times. When the calculation ends, the probability distribution of each node is output. The probability distribution conditions were identified according to the causal relationships among the nodes, and the data were recorded. Then, the CPT for all network nodes was obtained. Part of the CPT is shown in Figure 2.

The CPT describes the probability of occurrence of the child nodes under different parent node states. Because the four root nodes K1, K2, K3, and K4 have no parent root, their probability of occurrence is certain. The analysis and calculations in this study were all based on this CPT.

3. Data

The fundamental data used in this study came from 50,000 records of safety-inspection data of an elevator installation company from 2010 to 2017. Based on the safety risks observed and recorded by the company on a regular basis, it has been deemed one of the most effective programs for safety mitigation [13]. The record for each inspection includes the risk state of various checklist items such as human errors, environment, machinery, and organization. Each record also includes other information such as time, location, inspector, and elevator type. The company checklist contains 81 risk items, which are divided into four categories—fall protection, elevator control, control of energy transfer, and hazardous operations—each containing 12–30 hidden dangers (checklist items). The company policy rule stipulated that any risk found during an inspection should be rectified immediately. The company randomly investigated the safety risks at the site at least eight times per month using the safety audit checklist. By corporate regulation, 3–5 inspections occurred weekly, which could only be carried out by trained inspectors and were immediately logged into the safety-inspection system. When any hazards were found, they were recorded by the safety officer and confirmed by the corresponding supervisor. This double-check process guaranteed the quality of the records. Once the hazards were confirmed, the company policy enforced the elimination of

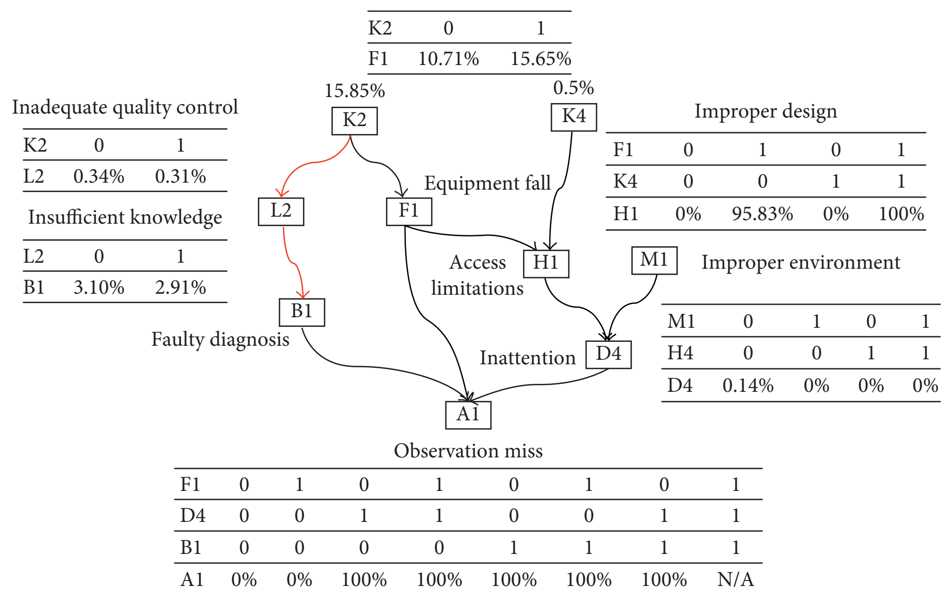


Figure 2: Parameter estimation for CPT (partial BN).

Table 1: Influence (probability increase) of root nodes on unsafe behavior.

PSF	Insufficient maintenance (K1)	Inadequate quality control (K2)	Improper management (K3)	Improper design (K4)
P(X1|PSF = no)	6.08%	3.34%	6.10%	6.07%
P(X1|PSF = yes)	7.08%	16.14%	6.10%	10.91%
PI*	16.4%	383.1%	0.00%	79.6%

*PI (probability increase) = [P(X1|PSF = yes) − P(X1|PSF = no)]/P(X1|PSF = no).

the hazard immediately upon the end of the inspection. In order to use more specifically targeted data, 39,691 records of vertical ladder construction were screened and qualified as the input data for this study.

4. Findings

4.1. Contribution of Improper Workplace Environment to Occurrence of Human Error. Although existing research reports absolute figures for the influence of improper design (root node K4) on human error, quantification of the effects of the other three root nodes (insufficient maintenance, K1; inadequate quality control, K2; and improper management, K3) on human error is necessary so that the existing research can be corroborated. With regard to these node variables, CPT provides the probabilities of parent nodes and those of the subnodes under different conditions, which to some extent are representative of conditions on-site. Therefore, from the assignment of the root nodes, the probabilities of the other nodes can be obtained. For example, when a workplace environment is improper, the root node is assigned as 1 (K4 = 1). The probability of unsafe behavior caused by human under the error sequence class under the assumption of an improper workplace environment can be calculated within a sequence class. Similarly, when the value is assigned as zero, the probability of unsafe human behavior under the assumption of a proper workplace environment can be calculated. Because this calculation is carried out without any change in the on-site work, the probabilistic influence of improper workplace environment on unsafe human behavior can be determined via comparison. When applied to all the root nodes, these calculations can also determine the influence of the other root nodes on human error.

The calculation results obtained for insufficient maintenance (K1), inadequate quality control (K2), improper management (K3), and improper design (K4) are shown in Table 1. Insufficient maintenance refers to poorly maintained equipment; temporary and permanent facilities may be improperly serviced during the initial construction stage, resulting in a disabled and nonfunctioning system. Inadequate quality control refers to defects in entities both tangible (such as devices) and intangible (such as rules), as well as insufficiency of resources and supplies. Improper management means ineffective organizational structure, responsibility allocation, and communication, including that for managing equipment, materials, and subcontractors. Improper workplace environment means defects in the configuration of construction materials and engineering techniques.

Table 1 shows the influence of the four root nodes on the estimated probability of unsafe human behavior, θ. These results show that the probability of human error increases from 6.07% to 10.91%, an increase of 79.6%, when the workplace environment fails. Under insufficient maintenance, on the contrary, the probability increases from 6.08% to 7.08%, an increase of 16.4%. Human error also increases when inadequate quality control exists, increasing from

3.34% to 16.14%, an increase of 383.1%. However, no change due to poor management is detected. These findings are discussed further in Discussion.

According to the results of the parameter estimation in this study, the probability of unsafe human behavior is 3.3% when none of the risks represented by the root nodes are present. In contrast, the probability of unsafe human behavior reaches 20.1% when all four root PSFs are present. Li et al. [20] developed a method for estimating the reliability of humans in construction engineering. In their estimation, the probability of human error was 6.3% when all of the root nodes remained within safe levels and reached 96.3% with all root nodes at unsafe levels. From the perspective of human reliability, the probability of human error is less than 10% in the circumstance of the nonpresence of any root node risks. However, for the case when all four risk conditions are present, the probability of unsafe human behavior found in this study (20%) is much lower than that in Li et al.'s study (96%). In practice, when multiple variables are at an unsafe level, humans will likely take precautions to reduce human errors rather than allowing them to continue out of control.

With the model estimation and CPT calculation, the influence of all nodes on the unsafe human behavior has been quantified. The result shows that the probability of human error within a class of error sequences increases by 79.6% when an improper workplace environment is present, ranking second among the four factors. Overall, workplace environment significantly influences unsafe human behavior both in absolute figures and in relative terms.

4.2. Path Analysis and Roles of Intermediate Nodes. To identify the paths that significantly influence human error, all the paths in the model were tested in terms of the workplace environment against human error and quantified using posterior predictive simulation. First, the intermediate nodes of the intended path were constrained to zero and the root node of interest (K4) was set to 1, and then, the conditional probability of human error was calculated. By comparing the result with the original "wrong sequence" value for the case in which K4 is set to 1 without any other constraints on the nodes, the value of the path's influence could be estimated. Then the paths that most significantly influence human error can be identified. The mechanisms (paths) by which an improper workplace environment invokes human error can thereby be clarified.

As nodes may be affected by many distant nodes, the influence of the paths must be separated from cross effects from outside the path. With regard to this cross-effect, this study also quantified the effects of root nodes other than those in the workplace environment. Once the path that significantly influences human error is identified, it is necessary to confirm whether the other root nodes (K1, K2, and K3) cross this path and to estimate their influence. If other root nodes exist that affect this path (K4), it is important to study the other root nodes to explain the mechanism by which improper workplace environment invokes human error.

Table 2: Probability of nodes in the presence of improper design (K4).

Model variables	Content	Probability (%)
K1	Insufficient maintenance	1.12
K2	Inadequate quality control	21.39
K3	Improper management	1.59
M1	Improper environment	5.18
L2	Insufficient knowledge	1.12
H1	Access limitations	0.07
D4	Inattention	49.75
G1	Inadequate procedure	50.87
J1	Communication failure	73.52
N2	Inadequate workplace layout	2.77
D1	Memory failure	1.43
A1	Observation miss	54.54
J2	Missing information	0.64
B1	Faulty diagnosis	70.02
X1	Wrong sequence (unsafe behavior)	10.90

The probability of each node in the presence of improper design (K4) can be calculated using the parameter estimation results and is given in Table 2. Among the intermediate nodes having a high probability of deficiency are inattention (D4), inadequate procedure (G1), communication failure (J1), and observation miss (A1). Note that not all of the real data were mapped onto nodes of the model; factors of human cognitive functions such as inattention (D4) and absence of observation (A1) were estimated with the data in the parent nodes using (3). The conditional occurrence probability of faulty diagnosis (B1) reaches 70% when the workplace environment fails. However, this result does not account for the entire conditional occurrence probability for improper workplace environment; the cross-effects of workplace environment, quality, maintenance, and management also need to be considered in order to describe the complex mechanism.

The first key finding from the path analysis for the roots is that some important nodes were found to serve as a bridge. For example, all the root risks (K1, K2, K3, and K4) create the condition of "improper environment" (M1). In particular, for each of the four root risks, the path having the greatest negative influence goes through node M1, resulting in differences in the probability of a human error [$\Pr(\Delta\tilde{y})$] of 5.57%, 23.57%, 6.55%, and 14.78%, respectively. For the problems corresponding to the nodes for insufficient maintenance (K1) and improper management (K3), all possible paths also pass through M1 (improper environment). However, its effect is not obvious, with the human error probability differences of only 5.57% and 6.55%, respectively. Further observation of the path influence for the remaining root nodes through M1 shows weak positive influence, which illustrates that when the workplace environment influence is transferred along the M1-related path, the effect of negative transfer dominates. On the contrary, G1 (inadequate procedure) is interconnected with the path having the greatest influence. The paths having the greatest positive influence that include root nodes K2 (inadequate quality control) and K4 (improper design) both go through

G1; their probability differences for human error are 9.42% and 14.61%, respectively. The other paths through G1 also show strong positive influence, which illustrates that when the influence of the improper workplace environment is transferred along the G1-related path, the effect of positive transfer dominates. The positive and negative relationships are further elaborated in Discussion.

The second key finding, through the crossover analysis of the paths of each of the four roots having the largest positive and negative influence, is that these paths are found to have high repeatability. Specifically, the positive maximum path from the K4 (improper design) node to the final behavior node exactly coincides with that from the K2 (inadequate quality control) node. In other words, all the middle nodes are exactly the same, which means that a strong interaction exists between K4 (improper design) and K2 (inadequate quality control). This result suggests that the influence of quality control should be considered when analyzing the positive mechanism for the influence of the workplace environment on human error. Furthermore, the negative maximum paths of the four root nodes intersect on exactly the same nodes, which indicates that the characteristics of M1 (improper environment) and of all the root nodes should be further elaborated to further demonstrate the influence mechanism.

4.3. Ranking of Mechanisms of Influence Given an Improper Workplace Environment. The failure of a workplace environment (in this case, improper workmanship in the workplace environment) under such a mechanism of influence causes the probability that workers will bypass the use of a safety harness to increase by 9.42%. Among all the paths, this mechanism has the highest probability of occurrence. Supporting the saliency of such a result, Li et al. [20] reported that human errors are mainly the result of workload fatigue due to workplace environment tasks. Although their results are consistent with the finding of this study, this study further demonstrates that insufficient information can also lead to failure of cognitive judgment. From the results of the path analysis, the process of influence of a company's workplace environment on human error may involve the following factors: the company's lack of standard procedures, the installation process, and the installation of lifeline anchorage points (improper design, K4). In addition, during actual installation, sufficient control over the construction method and quality of support points at the site may be lacking, causing the workers to decide for themselves how to perform the installation (inadequate quality control, K2). As a result, the location and structure of the support points may be too casual to allow the builders to determine whether they have sufficient support capacity. Workers performing work that requires a safety harness may find that the support capacity at the anchor point is problematic. If the regulations contain no standard measures instructing the workers on a course of action under such a circumstance (inadequate procedure, G1), the workers cannot obtain the needed information (missing information, J2). Hence, they may think that even if they use a safety harness, these measures would not help (faulty diagnosis, B1); thus, they may bypass the use of the safety harness (wrong sequence, X1). In summary, the human error "fall protection not used" has resulted from cognitive failure arising from information needed by the workers being missing because of incomplete procedures. According to the action-change and action-chain models proposed by Sato [42], failure states of the elements in a system can be transferred as in a chain. In other words, improper workmanship in the workplace environment (made evident as unreliable or unavailable component functionality) creates an environment that causes humans to deviate from predefined standards of performance or workmanship. This deficiency causes the procedure to fail to respond to practical needs by transferring the necessary installation information; thus, the failure state is transferred to the workers, which finally results in human error.

The mode of conduction along the abovementioned paths can be explained by the intuition that an improper workplace environment creates states that limit the working space or accessibility to the site. Most of these states are not normally introduced in the training materials for installation procedures formulated beforehand. The workers will face a completely different situation with no procedures or other information to instruct them regarding the proper way to deal with the new situation. In this case, from interviews with the workers, the authors learned that they are likely to deviate from standard operating procedures, thus risking human error. Although existing research provides little information on the means by which an uncertain process influences human behavior, there has been one study whose conclusion partly confirms this path: Gambatese and Hinze [11] believed that when a workplace environment is formed, construction processes are fundamentally determined. However, if the workplace environment does not transfer the detailed information to the construction stage, the site construction process will not be completely in accordance with the workplace environment expectation, leading to deviation between the plan and the actual states. Thus, the workers will be confronted with a scene different from that described in the standard procedure, causing them to operate arbitrarily and thereby increasing the probability of their choosing human error. This result indicates the necessity of the incorporation of "resilience" into the workplace environment. For instance, Weinstein et al. [43] collected and categorized many workplace environment recommendations from industry experience in which a specific fixed position of an anchor point for a lifeline was stipulated to ensure that protection is available when needed.

5. Discussion

5.1. Negative Correlations and Counterfactual Relationships. The results in the previous section show that all four root risks have the greatest negative influence going through node M1, resulting in differences in the probability of a human error [$\Pr(\Delta\tilde{y})$] of 5.57%, 23.57%, 6.55%, and 14.78%, respectively. What is the meaning of the negative relationships found in this study, and how should negative relationships among variables be interpreted? A good explanation should account for the lagging effects among the risks (nodes) that occur. The abovementioned model presenting the mechanisms of influence for a series of risks does not determine whether they occur simultaneously. It is possible that the predecessor risks may create certain limitations, remaining in a given state for a certain amount of time and thereby imposing constraints on the successor risks. In addition, as this research was conducted using a modified theoretical model combined with real data, the analysis given here does not purport to support a predefined causation but rather indicates the notion of a pair in a causal relationship. As such, the analysis explains certain features of causation. Negative correlations exist between the probabilities of some nodes, and improper workplace environment can be explained as the "malfunction of a desired state." Once this state is recorded, the hazard can be eliminated immediately upon discovery, leading to a reduction in the probability of occurrence of succeeding risks. For instance, an area of the workplace may have components with sharp edges (inadequate quality control, K2), materials piled up on the site (improper management, K3), or bare wires resulting from infrequently maintained lines (insufficient maintenance, K1), which can limit workers from performing construction in the area and force them to work near edges from which they may fall (inadequate workplace layout, N2). The relationships in the analysis can thus be interpreted as, "If any of these risks can be eliminated, the probability of succeeding risks can be reduced."

5.2. Role of Management. Numerous studies have been argued that management is a critical factor that can lead to human error. Now that the findings have shown that the influence of an improper workplace environment on human error prevails over that of improper management, the possible reasons can be presented as follows: First, "improper management" in this study refers mainly to defects in organizational management tasks, such as "no registration or control method for jumpers." When quality, maintenance, workplace environment, and other factors interact, the existence of management issues does not greatly influence the probability of occurrence of unsafe human behavior. Previous studies have shown similar findings. In an analysis of the causes of 224 actual accidents, Hecker et al. [44] found that no accident could have been prevented by simply making regulations and rules because most accidents were also related to factors such as workplace environment. Reason [2] proposed that builders are easily forced by changes in the site environment to violate existing rules. Thus, if they do not understand the mechanisms of occurrence and are simply directed by management, the effects are likely to be limited. Second, the result is limited by the scope of the model. Because the model emphasizes multiple factors relevant to human error in individuals, the psychological mechanism for a worker that is affected by the group is rarely mentioned. Meanwhile, Zhang [45] and Jiang [46] emphasized that such interactions can influence human errors. The role of management still has room for expansion. "Management" in this study refers to management of the organization and of the staff of a subcontractor (the elevator installation company) and mainly describes the task assignment, order, and takeover between organizers or inside the organization. However, management interfaces are only a marginal consideration in this study, reflected in behavior feedback and other management factors. Nevertheless, such interactive relationships can have some influence on unsafe human behavior. Because the current study aimed to observe the mechanism of influence of the workplace environment, in consideration of the interactions of other environmental factors with human error and the limitations of this model, the importance of organizational management work should not be overlooked.

6. Conclusion

Using elevator construction work as an example, this study has modified a human error model and conducted Bayesian parameter estimation and maximum likelihood estimation using real-world observational data. By comparing these with conditional probabilities, the influence of improper workplace environment on unsafe human behavior when interacting with other nodes was investigated with the proposed posterior predictive method. A cross-analysis method was adopted to reveal the most probable path for the influence of improper workplace environment on unsafe human behavior. This study has not only revealed a mechanism for the influence of improper workplace environment on human error but also presented an innovative analytical method for combining parameter estimation with a posterior predictive method.

However, this research is restricted by the following items, and thus, the results should be interpreted with caution. First, the study employed the data from a practical project safety check as the basis for computation, under a perfect-data hypothesis that assumes that every data record has perfectly described the occurrence of the various risks at the site. In reality, in a practical inspection, the inspector can make a mistake, may be limited by the staff's level of knowledge, or find ways to hide shortfalls, which can distort the data. Therefore, future studies should incorporate interview techniques or wearable devices to collect such information for more integrated study. Second, after the Bayesian parameter learning performed in this study, the point estimate for each node was calculated according to the output node CPT, but no probability distribution of the nodes was obtained. Thus, only the value differences were compared, and the current study could not compare paths or detect any sharp contrasts between the influences of various nodes. Future studies could utilize bootstrap methods and simulate probability distributions to compare the significance of the influence levels.

Data Availability

The authors worked with a reputable elevator company on a funded research project and thus being accessible to the data. In the agreement of their collaboration, any kinds of data including inspection table, records are owned by the company and thus being confidential to anybody else. The authors thank the readers for their understanding of the collaboration agreement.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Influencing Factors on Profit Distribution of Public-Private Partnership Projects: Private Sector's Perspective

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As an important issue in the public-private partnership (PPP) projects, the profit distribution has a critical impact on both the public and private sectors. Moreover, the influence of the private sector on the profit distribution of PPP projects cannot be ignored because the private sector are the implementers of PPP projects and responsible for the life-cycle performance and management of PPP projects. Therefore, this study aims at (1) investigating the influencing factors of the profit distribution of PPP projects from the private sector's perspective and (2) analyzing the relationships between the factors and the profit distribution by the qualitative comparative analysis (QCA). The results first showed that the five key influencing factors on the profit distribution from the private sector's perspective were the risk sharing, financing ability, investment, management ability, and effort level. Moreover, the results indicated that the risk sharing was the most important factor that had a positive impact on the profit distribution. Furthermore, the strong management ability and the high ratio of investment were identified as critical factors that led to a larger proportion of profits distributed to the private sector. In addition, the financing ability and the effort level of the private sector should also be considered in the profit distribution plan. The findings first contributed to the body of knowledge on the influencing factors of the profit distribution in PPP projects. In addition, this study is the first attempt of exploring the characteristics of the private sector under the context of profit distribution of PPP projects and using the QCA method to enrich the theoretical research. Thus, the findings would help the private companies improve their abilities and ensure their profits. Besides, the public and private sectors can make appropriate profit distribution proposals in practice based on the conclusion of this study.

1. Introduction

The public-private partnership (PPP) mode, which is the cooperation between the private company and the government, has been widely used for the development of various infrastructure projects all over the world such as the transportation, waste water treatment, and hospital [1, 2]. Moreover, the research on the PPP has been diversified in many aspects such as financing, laws, management, and contract standards [3]. Among these topics, the profit distribution of PPP projects, which means the sharing of profits between the public and private sectors, is the corn concern of both the public and private sectors [4]. The government cares about the saving of financial fund, while private companies pay attention to their own profits [5]. A balanced profit distribution plan has a critical impact on the achievement of a triple-win scenario among the public sector, private company, and the general community [6]. On the contrary, an unfair profit distribution may lead to the negative influence on a project's outcome and stakeholders. In addition, many factors, such as the equity structure, risk allocation, and management, can influence the profit distribution of PPP projects [7]. Because the private sector are the implementers of PPP projects and are responsible for the life-cycle performance and management of PPP projects [8], analyzing the critical factors influencing the profit distribution of PPP projects from the private sector's perspective is quite necessary. However, there is currently still a lack of such relevant research.

Therefore, the objectives of this study are to (1) investigate the influencing factors on the profit distribution of PPP projects from the private sector's perspective using document analysis and (2) analyze the relationships between the influencing factors and profit distribution results based on data from cases using the qualitative comparative analysis (QCA) method. The findings first contributed to the body of knowledge on the influencing factors of the profit distribution in PPP projects. Moreover, this study is the first attempt of exploring the characteristics of the private sector under the context of profit distribution in PPP projects. Thus, the findings would not only help the private companies improve their abilities and ensure their profits but also provide references for the public and private sectors to make appropriate profit distribution proposals in practice.

2. Literature Review

2.1. PPP Projects and the Profit Distribution

2.1.1. Concepts of PPP Projects. As an important and widely used mode for providing public infrastructure and service, the PPP mode is a working arrangement based on the mutual commitment between the private company and the government [9]. The public sector remains the guarantor and supervisor but not the provider anymore. Correspondingly, the private sector plays an increasingly important role in the financing, constructing, management, and operation of the projects [10]. Although there are many types of public-private arrangements, such as BOT, BOOT, and TOT [11], the fair sharing risks and profit distribution is the core principle of PPP [12]. Through PPP, the public sector aims at delivering the infrastructure early and achieving the value for money [13], maximizing the benefits of the public. On the contrary, the private sector cares more about the profits obtained by their companies from PPP projects. Thus, the profit distribution is a key issue in PPP projects for both the public and private sectors.

2.1.2. Profit Distribution of PPP Projects. The profit distribution means the allocation of the total profits of a PPP project between the public and private sectors. A fair profit distribution typically indicates the balance of the interests between the partners [2, 14]. The developments of PPP projects are complex because of the increasing number of participants and different targets from different participants [15]. Thus, making a scientific and proper profit distribution plan is hard but important and necessary. To achieve this objective, the precondition is to identify and analyze the factors influencing the profit distribution of PPP projects. First, the optimization of equity capital structure can balance the interests between the public and private sectors [14]. Second, a proper risk management framework helps to balance the benefits among the government, private partners, and end users [16]. Besides, a higher level of risk to a participant should lead to a higher share of revenues. Ashuri et al. [7] proposed a risk and revenue sharing mechanism that combined the risk sharing result with the profit allocation. In addition, the allocation ratio of additional profits in PPP projects is related to an investor's fair preference and effort level coefficient [17].

In view of the above, the profit distribution of PPP projects could be influenced by risk allocation, equity investment, management, and other factors. Currently, there is still a lack of research systematically analyzing factors influencing the profit distribution of PPP projects, especially from the private sector's perspective. Therefore, this study aims at filling this research gap.

2.2. The Private Sector in PPP Projects. In PPP projects, the private sector develops and operates the public infrastructure and services, which is previously the responsibility of the public sector in the traditional development mode [10]. Therefore, the abilities and influence of the private sector draw great attention from many researchers.

2.2.1. Abilities of the Private Sector. Tiong [18] analyzed the critical success factors for a private sector to win a tender of a PPP project, including entrepreneurship, leadership, financial strength, relationships management, and technical advantages. Moreover, Zhang [19] stated that the appropriate private sector should be selected from four aspects: (1) financial, (2) technical, (3) safety, health, and environmental, and (4) managerial. In addition, Kumaraswamy and Anvuur [20] proposed a framework for selecting the proper private sector with three criteria: technology, sustainability, and relationship. Besides, the performance in existing projects was also identified as a basic condition.

Considering the above, the financial, managerial, and technical abilities and the ability of relationship management as well as good experiences are all essential capabilities for the private sector to achieve a good PPP project.

2.2.2. Influence of the Private Sector. Simões et al. [21] claimed that the private sector's participation increased the efficiency according to the productivity and efficiency analysis results. Moreover, Liu et al. [8] believed that the private sector, which has a good experience, relevant knowledge, and communication skills, could increase the effectiveness and efficiency of the tendering process in PPP projects. Besides, the private sector's investment behaviors, such as the timing and capacity of investment and the claim of the toll rate, can be different because of the government incentives, improving the outcome of the project [22]. In addition, De Schepper et al. [15] indicated that a dynamic management tool considering the high complexity of PPP projects will achieve an effective management of the private sector so as to get a successful result.

On the contrary, after investigating 35 failed PPP projects, Soomro and Zhang [23] claimed that the improper decisions and actions of the private sector over a project were fatal factors leading to a projects' failure. After analyzing the failure mechanism of PPP projects, Zhang and Ali Soomro [24] discussed the causal relationship between the private sector and projects' failure using multiple regression path analysis. Furthermore, the opportunistic behavior of the private sector is also harmful to the outcome of a project

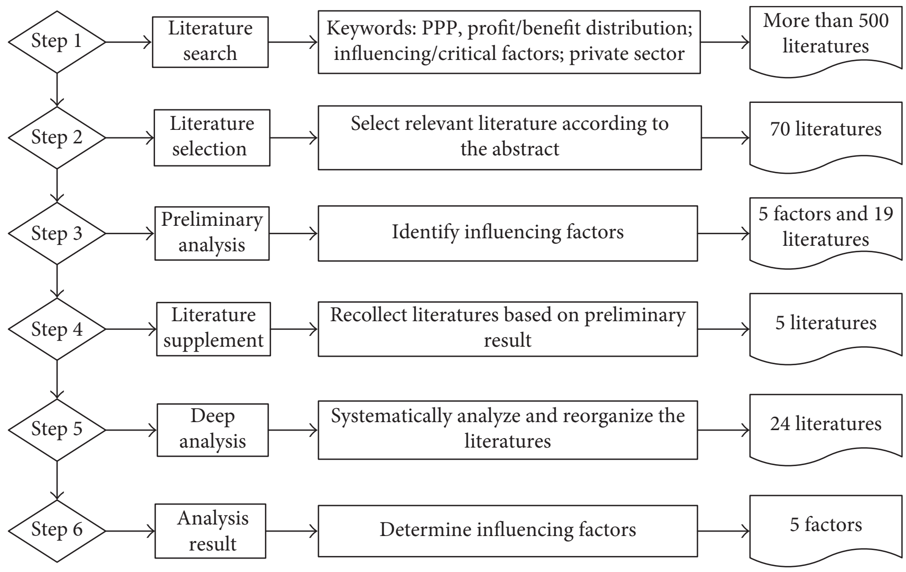

Figure 1: Document analysis process for identifying influencing factors.

and the public interests, which can be reduced by improving the profit distribution proportion of the private sector [25].

In view of the above, the private sector has been studied in many aspects. However, there is still a lack of research on the influence of the private sector on the profit distribution of PPP projects. Thus, identifying and analyzing the influencing factors on the profit distribution of PPP projects from the private sector's perspective can help to ensure the success of PPP projects and the profit of the private sector.

3. Methodology

3.1. Document Analysis. As an important part of qualitative analysis methods, the document analysis is a systematic progress to analyze the literatures [26]. To catch the original meanings of the literatures, this study conducted document analysis by the following systematic steps [27], as shown in Figure 1.

The document analysis was conducted through six steps. First, this study used the PPP, benefit/profit distribution, influencing/critical factors, and private sector as key words to search for the relevant literatures in the Scopus. At this stage, more than 500 literatures about these fields were listed. Second, this study screened the irrelevant papers through reading the abstract. After this step, about 70 literatures that are closely related to this topic were kept, while other papers with little correlation were omitted. Third, this study conducted a preliminary literature analysis to identify the influencing factors of the profit distribution on PPP projects from the private sector. Five influencing factors were summarized from these papers by skimming and scanning the full texts. Besides, 19 papers that have deep relationship with these factors were selected and organized together. Then, using the five factors as key words, respectively, 5 literatures were selected to supplement information. After that, a systematic and in-depth analysis was conducted relied on the 24 literatures. In this step, these literatures were reorganized according to the factors. Besides, the specific content of each factor was generalized based on these literatures. Finally, the five factors were determined scientifically.

3.2. Qualitative Comparative Analysis. To analyze the relationships among the factors and the profit distribution result, this study adopted the qualitative comparative analysis (QCA) method. QCA is a method combining qualitative analysis with quantitative calculation based on multiple cases [28].

3.2.1. Case Selection. To get a convincing result, the cases were selected according to two principles. On the one hand, the cases should have the same characters that can be treated as constant variables indicating the homogeneity of all cases [29]. On the other hand, these cases need to cover different fields and results, which can help to maintain the variety of the selected cases [30]. In addition, as a case-oriented method, the mechanical program, such as random selection, is not suitable. Therefore, the MDSO-MSDO (most different cases, similar outcome/most similar cases, and different outcome) procedure was used to achieve the systematic and scientific selection of cases. In this study, the outcome, which can also be called a dependent variable, is the result of the profit distribution in PPP projects. Moreover, the five influencing factors concluded by the literature analysis are descriptive variables. The focus of this research is that the changing of influencing factors from the private sector brings about different profit distribution results. Therefore, the MSDO procedure, which is used to search for the reasons for different profit distribution results in alike small samples, is appropriate [30].

To quantify these variables, the first step was to set up the binary threshold of the outcome and five descriptive variables. Second, every case was evaluated according to the binary threshold so as to assign "0" or "1" to each variable. Thus, a binary data sheet of the cases, which is the basic

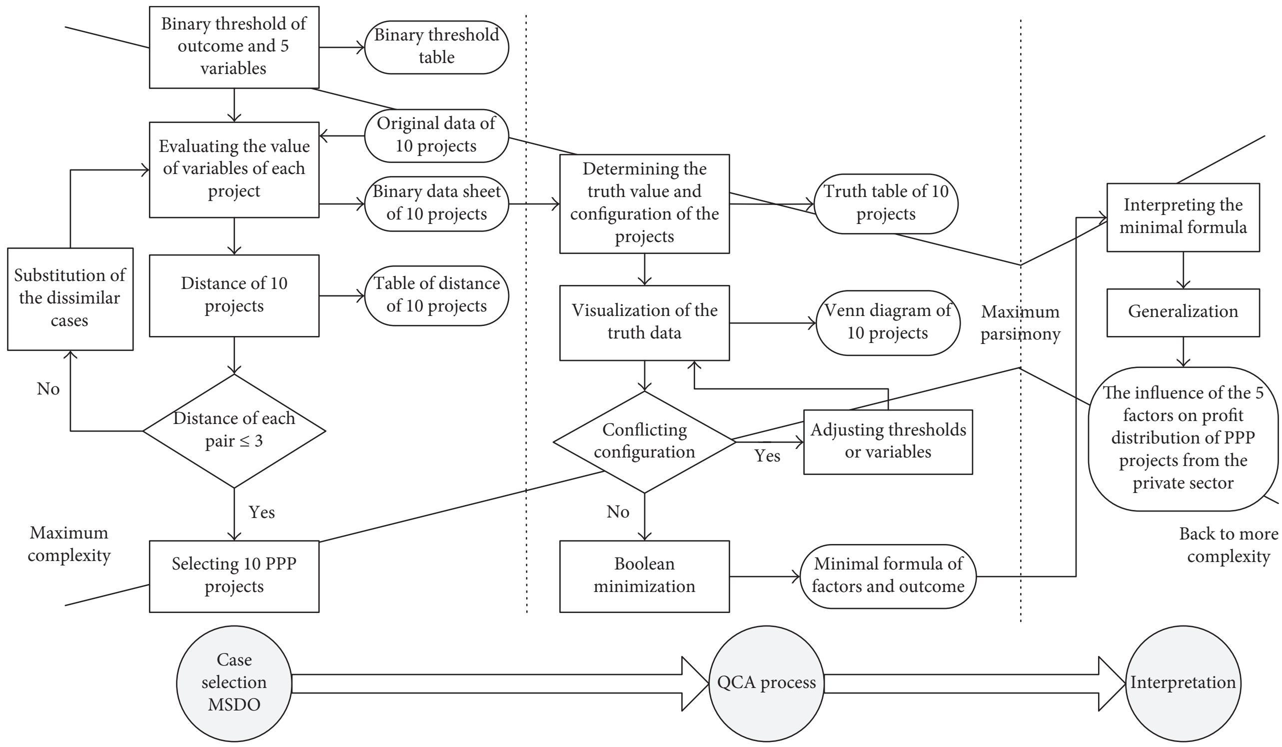

Figure 2: Process of QCA about the influencing factors of profit distribution.

information for both case selection and QCA process, was produced. Third, a Hamming distance, which is the number of variables with differing values, for each pair of cases was calculated. If the distance for each pair of projects is smaller than half of the descriptive variables, they are similar cases. By contrast, the distance that larger than 3 means the dissimilar cases [31]. Then, the dissimilar cases were replaced by a new project, and the binary data were renewed. After several cycles, 10 PPP projects were selected through the MDSO procedure.

3.2.2. QCA of 10 PPP Projects. After the selection of 10 PPP projects, the QCA method can be applied [30]. This study uses csQCA (crispy set QCA) to analyze the influences of factors from the private sector on the profit distribution of PPP projects because the descriptive variables and outcome can be expressed by the binary threshold clearly [30].

Based on the binary data sheet of case selection, the truth table of the 10 PPP projects can be concluded, which represents the configurations of these cases. The content of the table can be visualized in the Venn diagram. Without conflicting configuration in the 10 projects, there is no need to add variables or change projects. Then, through TOSMANA software, there are several formulae representing the configurations of cases. After the Boolean minimization, the minimal formula can show the relationships among the influencing factors and profit distribution outcome. Finally, the interpretation and generalization of the formulae contribute to the understanding of the results. To sum up, the QCA process can narrow the maximum complexity of the influence on the profit distribution of PPP projects from the private sector to the maximum parsimony situation, which are the minimal formula, and back to more complexity by the interpretation and generalization of the results [31]. The whole procedure is shown in Figure 2.

4. Results and Discussion

4.1. Determination of Influencing Factors. Through the deep analysis of literatures, five factors were identified as the most influencing factors on the profit distribution of PPP projects by considering the impact of the private sector, as shown in Table 1.

Based on the frequencies of these factors mentioned in the 24 literatures, the risk sharing in PPP projects was identified as the most important factor because it was mentioned 14 times in the 24 literatures, accounting for more than 30% of all the frequencies. Moreover, the financial ability and the investment of the private sector, which have a deep relationship with the finance of PPP projects, were identified as very essential factors, accounting for about 19% each. Besides, as an important skill of the private sector, the management ability was mentioned 8 times in the 24 literatures. In addition, the effort level of the private sector appeared for many times during the document analysis process. To sum up, the five factors were identified as critical factors that can represent the impact of the private sector on the profit distribution of PPP projects. The content of each factor is shown in Table 2.

First, as one of the most important parts of a PPP project, the party that takes the risks should adopt measures to control the risks, causing the increase of costs. Therefore, the amount of risks that is taken by each party has a closely relationship

Table 1: Results of literatures in the process of document analysis.

Number	Reference	Factors				
		Risk sharing	Financing ability	Investment	Management ability	Effort level
1	Tiong [18]	√	√	—	—	—
2	Dewatripont and Legros [32]	√	—	—	—	√
3	Zhang [19]	—	√	—	√	—
4	Zhang [33]	√	√	√	—	—
5	Zou et al. [16]	√	—	—	—	—
6	Ho and Tsui [34]	—	—	√	—	—
7	Ashuri et al. [7]	√	—	—	—	—
8	Sharma et al. [14]	—	—	√	—	—
9	Takashima et al. [35]	√	—	√	—	—
10	Jin and Zhang [36]	√	—	—	√	—
11	Valsangkar [37]	√	√	√	—	—
12	Soomro and Zhang [23]	—	√	—	√	—
13	Tang et al. [38]	—	√	—	√	—
14	Atmo and Duffield [39]	√	√	—	√	—
15	Fan and Zhai [40]	√	—	—	—	—
16	Khadaroo [41]	√	—	—	—	—
17	Wang and Liu [17]	√	—	—	—	√
18	Sharaffudin and Al-Mutairi [42]	√	√	—	√	—
19	Osei-Kyei and Chan [43]	√	√	—	√	—
20	Liu et al. [8]	—	—	—	√	—
21	Liu et al. [25]	—	—	—	—	√
22	Sokolitsyn et al. [44]	—	—	√	—	—
23	Li et al. [45]	√	—	√	—	—
24	Li and Cai [22]	—	—	√	—	—
	Frequency	15	9	8	8	3

Table 2: Influencing factors on profit distribution from the private sector.

Number	Factor	Content
1	Risk sharing	Amount of risks taken by the private sector and the costs of taking risk control measures
2	Financing ability	Ability of the private sector to finance, including the funding resources, rates, possibility of attracting investors, etc.
3	Investment	Investment ratio of the private sector in a project, that is, the amount of capitals invested in
4	Management ability	Ability of the private sector in the life-cycle management of a project
5	Effort level	Effort taken by the private sector for the success of a project, including the contributions except funds

with the profit distribution results [7]. Second, the financing ability of the core skills of the private sector has deep relationship with the adequacy of funds and influences the efficiency and effectiveness of the project [18]. Thus, the changing of this factor will lead to different total profits of a PPP project so as to impact the profit distribution result. Then, the investment is important for the life-cycle performance [22], shortage of which would cause the failure of a project and sharply decrease of profits. Therefore, embodying the investment factor in a profit distribution plan is necessary [14]. Moreover, the management ability of the private sector determines the effectiveness and efficiency of the development of a project [23]. In addition, the management ability has a close correlation with the life-cycle performance of a project [8], greatly affecting the profit distribution. Finally, a profit distribution plan need to consider the effort level of the private sector, which has social-economic effect on the project, leading to different profit results and distribution plans [17].

4.2. Impact of Influencing Factors on Profit Distribution

4.2.1. Case Description. According to the contents of variables and status quo of PPP projects, the binary threshold of these variables is shown in Table 3.

In PPP projects, the private sector and public sector are two parties who share the profits, implying that the basic profit distribution proportion is 50% [2, 40]. However, in many projects, the private sector is the major investor who shares more profits than the public sector. Considering this, this study adjusted the binary threshold of the outcome as 60%. Moreover, allocating risks to the private sector is an important approach of the public sector to use the PPP mode [46]. According to the information in real cases, the private sector often takes more risks than the public sector in PPP projects [32]. Thus, this study adjusted the threshold of risk as 70%. Besides, the private sector is the major investor in PPP projects [14]. Therefore, the binary threshold of the investment is adjusted as 70%. In addition, the financing ability, management ability, and effort level are important factors but hard to quantify by specific ratio. Thus, the thresholds of the three variables were determined by the degree rather than the proportion.

Table 3: Binary threshold of variables.

Variable	Value of variable 0	1
Profit distribution	Profit distributed to private sector is smaller than 60%	Profit distributed to private sector is larger than 60%
Risk sharing	Risk allocated to private sector is smaller than 70%	Risk allocated to private sector is larger than 70%
Financing ability	Financing ability is weak	Financing ability is strong
Investment	Investment of private sector is smaller than 70%	Investment of private sector is larger than 70%
Management ability	Management ability is weak	Management ability is strong
Effort level	The effort level is low	The effort level is high

Table 4: Basic information of 10 PPP projects.

Case ID	Title	Total investment (billion yuan)	Mode	Concession period
1	Beijing Metro Line 4	2.4	BLT + LDOT	2006–2036
2	Zhongdu medical and nursing combined project	0.10	BOO	2016–2046
3	Luoyang ancient city protection and renovation project	1.4	BOT + TOT + ROT	2016–2036
4	M6 Toll Road	1.7	PFI	2000–2053
5	Delhi Airport	79	BOT	2005–2024
6	Xinyi sewage treatment plant PPP reconstruction project	0.05	ROT	2015–2040
7	Intelligent parking system in Hongshan district	0.16	DBFOT	2016–2041
8	Rehabilitation center for disabled persons in Juye county	0.02	BOT	2015–2045
9	Water diversion project in Ningyang	0.21	BOT	2015–2045
10	Hangzhou Metro Line 1	3.5	BOT	2008–2033

Table 5: Binary data of variables in 10 PPP projects.

Case ID	Factors: Risk sharing	Financing ability	Investment	Management ability	Effort level	Profit distribution
1	0	1	0	1	1	0
2	1	1	1	1	1	1
3	1	1	0	1	1	1
4	1	1	1	1	1	1
5	1	1	1	0	1	0
6	0	0	0	1	1	0
7	1	0	1	0	0	1
8	1	1	1	1	0	1
9	1	1	0	1	1	1
10	0	1	0	1	1	0

Based on the MDSO procedure, this study chose 10 PPP projects covering different areas, sectors, and modes to analyze [47–50]. The basic information is shown in Table 4.

Based on the threshold values of the variables, this study analyzed the identified PPP cases and generated the binary data of the outcome, as shown in Table 5.

The results showed that the binary data of Zhongdu medical and nursing combined project (Case ID = 2) and M6 Toll Road (Case ID = 4) were all 1. The other eight projects had one or more different values. Subsequently, this study applied csQCA using these data.

4.2.2. Results of QCA. Through the combination of the projects that have same situation, this study generated the truth table, as shown in Table 6. This table shows all the configurations.

The results showed that there were seven different configurations because cases 1 and 10, cases 3 and 9, and cases 2 and 4 have the same value of all variables, respectively. In the seven configurations, there was no confliction, indicating that there is no need to adjust the variables and their thresholds. Besides, this study visualized the configurations by the Venn diagram, as shown in Figure 3.

The green area indicates configuration [1], which means a project had a negative profit distribution result (profit distributed to private sector is smaller than 60%); the red area indicates configuration [0], which shows that the positive profit distribution result (profit distributed to the private sector is larger than 60%). The white area is the remainders of

Table 6: Truth table of 10 PPP projects.

Case ID	Risk sharing	Financing ability	Investment	Management ability	Effort level	Outcome
6	0	0	0	1	1	0
1 and 10	0	1	0	1	1	0
7	1	0	1	0	0	1
3 and 9	1	1	0	1	1	1
5	1	1	1	0	1	0
8	1	1	1	1	0	1
2 and 4	1	1	1	1	1	1

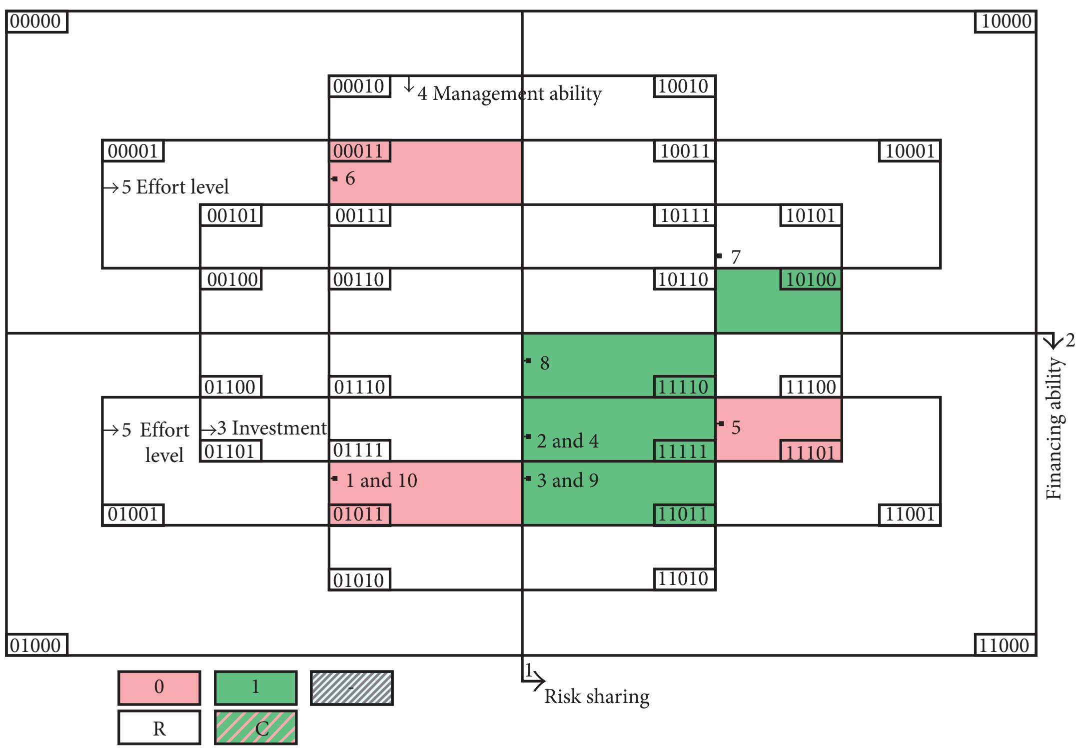

Figure 3: Venn diagram of 10 PPP projects. 0: negative outcome; 1: positive outcome; R: remainders of logic; C: conflicting configuration.

logic, implying the field that the cases cannot represent. It is a common situation that there are many remainders due to the limitation of the number of projects. Therefore, it is necessary to include the remainders in the minimization process to simplify the formulae [30].

Based on the information above, the results can be got by TOSMANA. To show the impact of the factors clearly and comprehensively, these configurations were minimized as formulae. The results were discussed as follows.

(1) Result of Configuration [1]. The minimization of configuration [1] including the remainders is summarized in Table 7.

There were four formulae of configuration [1] from cases 2, 3, 4, 7, 8, and 9, whose outcomes were positive. The results showed that the risk sharing, management ability, and investment had an important and positive impact on the profit distribution result. The effort level and financing ability had value of {0}, indicating that they did not have an essential positive influence on the result. Through the Boolean minimization process, the four formulae can be simplified to one minimal formula, which can also be called the Boolean expression, as shown:

$$\begin{aligned}&\text{Risk sharing }\{1\}\times\text{management ability }\{1\}\\&\quad+\text{ risk sharing }\{1\}\times\text{ financing ability }\{0\}\\&\quad\times\text{ investment }\{1\}\times\text{effort level }\{0\}.\end{aligned}\tag{1}$$

(2) Result of Configuration [0]. On the other hand, as for configuration [0], the result of minimization is shown in Table 8.

The two formulae represent the results of cases 1, 5, 6, and 10. The results showed that the profits distributed to the private sector are smaller than 60%. It indicated that the negative result of the risk sharing and management ability led to the negative outcome of the profit distribution for the private sector, while the effort level and financing ability may not have critical influences. Besides, investment variable is

Table 7: Results of configuration [1].

Formula 1	Effort level {0}	+	Risk sharing {1}, management ability {1}
Case ID	(7 + 8)	—	(2, 4 + 3, 9 + 8)
Formula 2	Risk sharing {1}, financing ability {0}	+	Risk sharing {1}, management ability {1}
Case ID	(7)	—	(2, 4 + 3, 9 + 8)
Formula 3	Risk sharing {1}, management ability {1}	+	Financing ability {0}, investment {1}
Case ID	(2, 4 + 3, 9 + 8)	—	(7)
Formula 4	Risk sharing {1}, management ability {1}	+	Financing ability {0}, management ability {0}
Case ID	(2, 4 + 3, 9 + 8)	—	(7)

Table 8: Results of configuration [0].

Formula 1	Risk sharing {0}	+	Financing ability {1}, management ability {1}
Case ID	(1, 10 + 6)	—	(5)
Formula 2	Risk sharing {0}	+	Management ability {0}, effort level {1}
Case ID	(1, 10 + 6)	—	(5)

not in the formulae, indicating that the negative outcome does not have a direct relationship with this factor. After the Boolean minimization, the minimal formula can be seen as:

$$\begin{aligned}&\text{Risk sharing } \{0\} + \text{financing ability } \{1\}\\&\times \text{management ability } \{0\} \times \text{effort level } \{1\}.\end{aligned} \tag{2}$$

4.3. Discussion of the Results

4.3.1. Configuration [1]. In configuration [1], the result can interpret the relationship between the influencing factors and the positive profit distribution result, which means the private sector can get more than 60% profits in PPP projects. Equation (1) can be explained in the following.

The private sector which (1) takes more than 70% risks and has a strong management ability OR (2) takes more than 70% risks and affords more than 70% of total investment without strong financing ability and high effort level can receive more than 60% profits in PPP projects.

This formula showed that the risk sharing had the most important impact on the profit distribution of PPP projects, indicating that the private sector who takes more risks should share more profits. This result coincided with the result of the literature analysis [7]. Moreover, the management ability was identified as an essential factor. The private sector with a strong management ability should get more profits because the private sector can ensure a good performance of a project. This opinion was also supported by Soomro and Zhang [23]. Besides, the investment had a close relationship with the profit distribution result. A large proportion of investment means a large ratio of profit distribution, which satisfies the basic rule of projects that equity investment and profit distribution should be balanced [14]. However, this study identified that a strong financing ability and effort level were not so important when risk allocated to the private sector is larger than 70% and investment of the private sector is larger than 70%. Therefore, the financing ability and effort level were identified as relevant but not decisive influencing factors on the profit distribution.

4.3.2. Configuration [0]. Configuration [0] means that the private sector gets smaller than 60% profits in PPP projects. Thus, the minimal formula represents the combination of factors that leads to this result. Equation (2) can be interpreted in the following.

The private sector which (1) burdens smaller than 70% risks OR (2) has a weak management ability with strong financing ability and high effort level can just obtain smaller than 60% of total profits.

This equation showed that a small ratio of risk sharing led to a small part of profit distribution, indicating the direct positive relationship between the risk sharing and the profit distribution. Moreover, the management ability was identified as a very necessary factor that had a negative influence on the profit distribution result. The private sector which has a strong financing ability and high effort level cannot guarantee a high proportion of profit distribution due to the weak management ability. The results of this study also implied that the financing ability and effort level were not as important as the management ability because they cannot bring a different profit distribution result without the change of the management ability.

To sum up, the two minimal formulae of contradict configurations showed the same relationships between the influencing factors and the profit distribution of PPP projects. On the one hand, the risk sharing was identified as the most important factor that had a positive impact on the profit distribution. Moreover, the management ability and the investment of the private sector were identified as two very critical factors that had a positive influence on the profits distributed to the private sector. On the other hand, the financing ability and effort level of the private sector were identified not as important as the three factors mentioned above for the profit distribution of PPP projects, indicating that they cannot lead to a different profit distribution result without considering the other three factors. Therefore, the private sector needs to pay more attention to the risk sharing ratio, the equity investment proportion, and the improvement of the management ability rather than just focusing on the raising of the financing ability and effort level to ensure the success of PPP projects and the fair profit distribution.

5. Conclusion

Profit distribution is an essential issue in a PPP project, which has important influence on both the public and private sectors. As the implementer of a PPP project, the private sector is responsible for the life-cycle performance and management that have direct relationship with the profit and its distribution. Therefore, this study analyzed the influencing factors on profit distribution of PPP projects from the private sector's perspective. Through document analysis, this study identified five factors. Furthermore, the results of QCA indicate that the risk sharing is the most important factor which has a positive impact on the profits obtained by the private sector. Moreover, management ability and investment are also critical factors that have positive influence on the profit distribution. Besides, financing ability and effort level also should be considered, but they do not have a decisive impact on the profit distribution. The findings first contributed to the body of knowledge on the influencing factors of the profit distribution in PPP projects. In addition, it is the first attempt of exploring the characteristics of the private sector under the context of profit distribution of PPP projects and using the QCA to enrich the theoretical research. Thus, the findings would help the private sector improve their abilities and pay more attention on the risk sharing and equity investment of PPP projects to ensure profits and promote the success of projects. Besides, the public and private sectors can make appropriate profit distribution proposals in practice based on the conclusion of this study.

Although the objectives of this study were achieved, there are still some limitations. First, the major influencing factors determined through the comprehensive literature review may not cover all the possible aspects. Second, due to the limitation of cases in the csQCA procedure, some other areas and fields are not covered. To overcome these limitations, further investigation on the influencing factors will be applied to expand the factors comprehensively. Moreover, future research will select more proper PPP projects from other areas and fields and rectify the conclusion, making the identified relationships more convincing and widely adaptable.

Data Availability

The cases in this study come from the online database of Public Private Partnership Projects in China. The data can be obtained through the following link: http://www.cpppc.org:8082/efmisweb/ppp/projectLibrary/toPPPList.do.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

A Decision Model Assessing the Owner and Contractor's Conflict Behaviors in Construction Projects

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Considering the effects of the contractor's conflict behaviors on the project benefit, a decision model between the owner and contractor's conflict behaviors in construction projects was constructed using the principal-agent theory and game theory. The model was analyzed under nonconflicting and conflicting conditions, and a numerical simulation and example analysis were proposed to verify the constructed model's conclusion. The results showed that the effort levels of the owner and contractor not only relate to benefit-sharing coefficient and effort outcome coefficient but also depend on the contractor's ability of converting the conflict into benefit and the loss caused by conflict behaviors. A higher ability of converting conflicts into benefits and lower levels of the loss caused by conflict behaviors for the contractor lead to lower levels of the net benefit of the owner, conversely higher levels of the net benefit of the contractor. Balancing the contractor's ability of converting conflicts into benefits and the loss caused by conflict behaviors lead to a more reasonable risk allocation between the owner and contractor, improving the effort level and net benefit. To add value to the construction project, the owner should establish an impartial and reasonable benefit-sharing mechanism, optimize the owner and contractor's resource arrangement, maximize the positive effect of conflict on project benefits, and avoid the negative effect of conflict. Few studies to date have investigated the effects of conflict behaviors on project benefits in terms of modeling and simulation in construction projects. As such, this study bridges this gap and contributes significant theoretical and practical insights about managing conflict behaviors in an interorganizational context, thus enhancing performance in construction projects.

1. Introduction

A typical construction project involves numerous project-based organizations, including the owner, the contractor, the subcontractor, the designer, and the consultant [1]. This creates a complex adaptive system with common objectives. The resources exchange and knowledge transfers occur between different participants during the project implementation. The heterogeneity of diverse participants inevitably leads to project conflicts. Losses caused by conflicts with untimely and inappropriate solutions account for approximately 3–5% of the total project investment [2]. Project conflicts involving project-based organizations occur along with the project life cycle occur from the initial stage to the operational stage. Because of these conflicts, project-based organizations experience an increasingly negative relationship, particularly between the owner and the contractor [3]. These adversarial behaviors include disparities between the owner and contractor, the objective conflict between the owner and contractor, and contention about resources based on different objectives. These behaviors consistently lead to disputes and negotiations between the owner and contractor, making it difficult to achieve an ideal cooperative effect [4]. Furthermore, these adversarial behaviors consistently lead to time and cost overruns, and complicate achievement of project objectives [5]. A critical factor for these behaviors is the absence of a conflict management mechanism, especially between the owner and contractor.

Therefore, more attention should be paid to investigate the occurrence of conflicts and mechanisms for managing it.

Managing construction projects inevitably involves contracts between the owner and contractor. Contracts are usually incomplete due to the inherent nature of construction projects; these projects have complex and uncertain transactions and processes, result in single products, and are unique—they only happen once [6]. These contracts significantly impact project success, particularly on projects involving more complex construction technologies and more specific divisions of work. All the efforts of project-based organizations are centered on project performance; inconsistencies in objectives, knowledge, and benefits lead to conflicts, thereby negatively impacting performance [7, 8]. Project participants are interdependent of each other, consistently leading to conflicts due to the diversity of knowledge and benefits [9]. Furthermore, the different core capabilities, information asymmetry, and unclear rights and responsibilities between participants also lead to conflicts [10].

This study constructed a decision model using game theory to examine conflict behaviors between the owner and contractor. In this model, the contractor is assumed to trigger the conflict behavior. The owner receives and responses to the conflict behavior. Therefore, the model can be used to assess: (i) under what conditions the contractor will trigger the conflict behavior; (ii) under what conditions the contractor can obtain a benefit from the conflict behavior; and (iii) how the owner can guard against the loss caused by the conflict behavior. Previous studies focused on the factors influencing conflicts and their effects on performance using empirical data. Few studies, however, have investigated the internal mechanism in terms of modeling and simulations in construction projects. This study bridges this gap and contributes significant theoretical and practical insights about conflicts occurring in an interorganizational context. These insights can enhance management performance in construction projects.

2. Literature Review

Conflict is a phenomenon that occurs when there are different beliefs, thoughts, and benefits between two or more individuals and is a complicated social and psychological phenomenon involving different levels and dimensions [11]. These different types and levels of conflict can interact and be interdependent [12]. Recently, researchers have introduced conflict theory to the field of construction project management. This study area has emerged because of the interdependencies and diversity between participants and imperfect management mechanisms, which may cause conflicts in construction projects [13].

The traditional definition of conflict emphasizes the opposition of objectives within a competitive background, and proposes that conflict originates from the opposite relationships with respect to benefits. Resource scarcity and the divergence of objectives are baseline factors assumed by this definition. The main result is that one party achieves its own objectives at the cost of other party's benefit. Conflict behaviors between an owner and contractor, the research object for this study, reflect a type of interorganizational conflict, namely, the conflict behavior between stakeholders in construction projects. Sources of conflicts in construction projects include limited public resources, different understandings of the project plan, and different task priorities [14, 15]. Additionally, the industrial characteristics of the building industry create sources of conflicts, including the discreteness of the construction link, low efficiencies, and cost overruns [16]. Therefore, conflict in construction projects is an interaction between different participants with different perceptions and viewpoints on a process or task. Conflict results from participant-related factors, project-related factors, and issues related to communication, benefit allocation, and trust. The background of projects provided a suitable environment to analyze conflict, because conflicts in construction projects are behaviorally related, and significantly affect performance.

Conflict can have constructive and destructive effects on performance. In construction projects, the traditional view of conflict is that it causes destructive effects. Xue et al. [17] proposed that performance is an interactive result of collaboration between multiple parties; because conflicts hinder collaboration, they are detrimental to performance. Conflicts can strain the owner and contractor relationship, impeding effective communication, and resulting in cost and time overruns, and low quality and satisfaction [18, 19]. However, the specific tasks of the project were unconventional. Conflicts can provide different views and knowledge with which to address tasks, improving decision quality [20, 21].

The effects of conflicts on performance may relate to management strategies; different strategies have different results [22]. Chen [23] explored the positive and negative effects in project value creation and found that the total life cycle adjusted the task conflict and project value. Anderson and Polkinghorn [24] discussed the importance of the conflict resolution skills and methods in constructing the Woodrow Wilson bridge; they concluded that process conflict had the greatest influence on performance. Brockman [25] surveyed 74 participants in different construction projects; 56% of respondents proposed that relationship conflict had destructive effects on performance. Puck and Pregernig [26] conducted a long-term survey of 92 construction teams, arguing that different types of task conflicts had different effects on performance. Chen et al. [3] concluded that conflicts between the owner and contractor were represented by an inverted U shape on cost performance; only moderate degrees of conflict could improve performance. Chen et al. [27] proposed that emotional conflicts effectively mediated decisions and philanthropic paternalism, using empirical data from 108 top managers. Wu [28] found that process and relationship conflicts were negatively related to project success, and task conflict contributed to project success. Therefore, there is still equivocal how conflicts affect performance in construction projects; for example, there is inadequate information about the internal interaction mechanism of conflict. Researchers have validated the constructive and destructive effects on performance using empirical data; however, the interaction mechanism still needs to be discovered and analyzed. Modeling and simulation methods are effective tools to uncover the internal mechanism, due to the inherent nature of construction projects.

This study assumed that the contractor is the triggering party and can trigger conflicts through claims and project changes [29]. The owner directly bears the consequence of conflicts, while conflict behaviors can be restrained through reward and penalty mechanism signed in contracts [30]. The contractor experiences two consequences of conflict behavior: gain or lose. Therefore, this study constructed a decision model using game theory to analyze the internal mechanisms of conflict behaviors on performance. The model analysis and conclusions can clarify the effect of conflict on performance, and contribute to the development of effective conflict management strategies. This study contributes significant theoretical and practical insights to the existing body of knowledge on conflict management. This study provides a useful reference for project managers maximize the advantages of the positive effects of conflicts, and avoid the negative effects of conflicts.

3. Model Description and Solution

3.1. Model Description. Assume there are two equal project-based organizations: the owner and the contractor. These organizations cooperate with each other to achieve the successful delivery during project implementation. Conflicts between the owner and contractor consistently occur due to the temporary and dynamic nature of cooperation. This study does not consider the time value of money and proposes the following hypotheses:

(i) The owner is risk-neutral and the contractor is risk-averse. The effort levels of the contractor and owner are e_1 and e_2, respectively. The functions of the cost of effort for the contractor and owner are expressed as follows:

$$C(e_i) = \frac{1}{2}e_i^2 \quad (i = 1, 2). \tag{1}$$

In this study, the parameter e_i is not limited to $e_i > 0$, which means the effort levels of the contractor and owner can be less than zero. If this occurs, the cooperation between the contractor and owner is negative, with neither being willing to allocate resources. The coefficients of the cost of effort for the contractor and the owner are the same and are assigned as one. Generally, the coefficients of the cost of effort are not the same and can be other values. This study focuses on the effects of conflicts on performance; as such, the influences of the coefficients of the cost of effort are not included.

(ii) Assume the contractor and owner can balance their effort level. The project outcome function can be written as [31]

$$R(e_1, e_2) = \kappa_1 e_1 + \kappa_2 e_2 + \varepsilon. \tag{2}$$

In this expression, the parameters of $\kappa_1 > 0$ and $\kappa_2 > 0$ are the outcome coefficients of effort levels of the contractor and owner. The coefficients reflect their integrated technology and management level. This is manifested by the ability to transfer input resources to outcomes and is related to staff quality, operational level, and technological ability [32]. The contractor and owner cannot directly observe each other's effort level; the levels can be evaluated based on the input resources and the achievement of objectives. The parameters e_1, e_2, and ε are mutually independent. The parameter ε is normally distributed as $N(0, \sigma^2)$, reflecting the influence of the external uncertainty on the outcome function.

(iii) Assume the owner provides a linear incentive contract for the contractor, written as $S = \Omega + \beta R(e_1, e_2)$. In this equation, the parameter Ω is a fixed reward the owner provides the contractor. This reward is a constant and cannot stimulate the contractor to adopt a higher level of effort. Thus, the value can be assigned to zero [33]. The parameter β is a coefficient of the project outcome sharing and is within the range $0 \le \beta \le 1$. This range reflects the incentive degree of the owner [34]. Additionally, this study focuses on conflict behaviors between the owner and contractor. This is a type of cooperative conflict because the owner and contractor cooperate to achieve successful project delivery, while also maximizing their own benefits. In this situation, inconsistent objectives may lead to conflict behaviors. This study focuses on conflict behaviors during the construction stage, when the contractor has superior information and can trigger conflicts through project changes and claims. Thus, the contractor is the party that can trigger conflicts. In contrast, the owner can only respond to the conflict based on the conflict type and the results.

(iv) When the contractor adopts conflict behaviors, the contractor benefits in two ways. One is the contractual coefficient of benefit sharing (β) and the other is the benefit converted through the conflict. Assuming the benefit converted through the conflict depends on the effort levels of the contractor (e_1) and the owner (e_2) and the coefficient (μ) of converting conflicts to benefits for the contractor ($0 < \mu < 1$). Therefore, the benefits converted through the conflict can be presented as $\mu e_1 e_2$, which are paid by the owner. The coefficient of converting conflicts to benefits for the contractor (μ) reflects the bargaining ability of the contractor who is adopting conflict behaviors. The coefficient relates to the qualification, similar project experiences, and reputation. Additionally, the owner can adjust the level of effort to affect the benefits converted through the conflict. Generally, high values for the coefficient of converting conflicts to benefits and efforts of the contractor lead to lower levels of effort for the owner, even a negative value of the effort level.

Furthermore, when the contractor adopts conflict behaviors, the owner must spend time to address the conflict and prevent the loss. This may lead to the owner distrusting the contractor. Under this condition, adopting conflict behaviors may lead to both current and future losses for the contractor. Current losses include failures of project changes and claims and accelerated costs due to an extended conflict resolution period. Future losses include losing opportunities for future cooperation, and a lower reputation due to an unsuitable conflict environment. Assume the coefficient of loss caused by conflict behaviors is η and satisfies the condition of $0 < \eta < 1$. The loss caused by conflict behaviors is ηe_1; this variable relates to the effort level, input resources, and cooperative attitude of the contractor. This reflects the fact that higher levels of effort lead to higher levels of loss for the contractor adopting conflicts. The contractor may trigger conflict behaviors when $\mu e_1 e_2 > \eta e_1$. In other words, the contractor triggers conflict behaviors only when the contractor estimates the benefits exceed the loss brought by the conflicts.

Therefore, when there are conflict behaviors between the owner and contractor, the function of net benefits of the contractor can be expressed as

$$U_1 = \beta(\kappa_1 e_1 + \kappa_2 e_2) - \frac{1}{2}e_1^2 + \mu e_1 e_2 - \eta e_1 - \frac{1}{2}\rho\beta^2\sigma^2. \tag{3}$$

The function of net benefits of the owner can be written as

$$U_2 = (1-\beta)(\kappa_1 e_1 + \kappa_2 e_2) - \frac{1}{2}e_2^2 - \mu e_1 e_2 + \eta e_1. \tag{4}$$

The function of project outcome can be written as

$$U = \kappa_1 e_1 + \kappa_2 e_2 - \frac{1}{2}e_1^2 - \frac{1}{2}e_2^2 - \frac{1}{2}\rho\beta^2\sigma^2. \tag{5}$$

3.2. Model Solution

3.2.1. Solution under Nonconflicting Behavior Condition. To compare the effects of conflict behaviors on performance, the proposed model first considered nonconflicting behaviors. Under this condition, the function of net benefits of the contractor and the owner and the function of project outcome can be written as

$$U_1 = \beta(\kappa_1 e_1 + \kappa_2 e_2) - \frac{1}{2}e_1^2 - \frac{1}{2}\rho\beta^2\sigma^2, \tag{6}$$

$$U_2 = (1-\beta)(\kappa_1 e_1 + \kappa_2 e_2) - \frac{1}{2}e_2^2, \tag{7}$$

$$U = \kappa_1 e_1 + \kappa_2 e_2 - \frac{1}{2}e_1^2 - \frac{1}{2}e_2^2 - \frac{1}{2}\rho\beta^2\sigma^2. \tag{8}$$

The first partial derivatives of e_1 and e_2 were calculated, and the values were set to zero. This led to the following equation:

$$\begin{aligned}\frac{\partial U_1}{\partial e_1} &= \beta\kappa_1 - e_1 = 0,\\ \frac{\partial U_2}{\partial e_2} &= (1-\beta)\kappa_2 - e_2 = 0.\end{aligned} \tag{9}$$

We solve the above simultaneous equation for e_1 and e_2 as follows:

$$\begin{aligned}e_1^{**} &= \beta\kappa_1,\\ e_2^{**} &= (1-\beta)\kappa_2.\end{aligned} \tag{10}$$

According to the extremum attributes of functions, the second partial derivatives of U is $\partial^2 U/\partial\beta^2 = -\kappa_1^2 - \kappa_2^2 - \rho\sigma^2 < 0$. Substituting (10) into (8), we calculated the partial derivatives of β. The value was then set to zero and solved as

$$\beta^{**} = \frac{\kappa_1^2}{\kappa_1^2 + \kappa_2^2 + \rho\sigma^2}. \tag{11}$$

3.2.2. Solution under Conflicting Behavior Condition. For (3) and (4), the first partial derivatives of e_1 and e_2 were calculated, respectively. The values were then set to zero, and the following equation was obtained:

$$\begin{aligned}\frac{\partial U_1}{\partial e_1} &= \beta\kappa_1 - e_1 + \mu e_2 - \eta = 0,\\ \frac{\partial U_2}{\partial e_2} &= (1-\beta)\kappa_2 - e_2 - \mu e_1 = 0.\end{aligned} \tag{12}$$

To solve the above simultaneous equation for e_1 and e_2, we obtain

$$\begin{aligned}e_1^{*} &= \frac{(\kappa_1\beta - \eta) + \mu\kappa_2(1-\beta)}{1+\mu^2},\\ e_2^{*} &= \frac{\kappa_2(1-\beta) - \mu(\kappa_1\beta - \eta)}{1+\mu^2}.\end{aligned} \tag{13}$$

According to the extremum attributes of functions, the second partial derivatives of U was $\partial^2 U/\partial\beta^2 = -((\kappa_1^2 + \kappa_2^2)/(1+\mu^2)) - \rho\sigma^2 < 0$. The partial derivatives of β were calculated by substituting (13) into (5). The value was then set to zero and solved as

$$\beta^{*} = \frac{\kappa_1^2 + 2\mu\kappa_1\kappa_2 - \eta\kappa_1}{\kappa_1^2 + \kappa_2^2 + \rho(1+\mu^2)\sigma^2}. \tag{14}$$

4. Model Analysis and Simulations

4.1. Model Analysis

Proposition 1. *Under the condition of nonconflicting behaviors, the effort levels of the contractor and the owner do not relate to one another. Instead, they are related to their own outcome coefficients of effort levels and the contractual coefficient of benefit sharing. For the contractor, a high level of benefit sharing provided by the owner and a high outcome coefficient contribute to a high effort level. When the project benefit is fixed, a high level of benefit sharing leads to a low benefit for the owner. This leads to a low effort level by the owner. Therefore, when designing the incentive mechanism for the project operation, the owner needs to determine a reasonable coefficient of benefit sharing for the owner, based on the outcome coefficient and contractor effort. In this situation, if the owner adopts an optimal incentive method for the contractor, the specific project can achieve a stable and balanced* *state. It is relatively easy to design an incentive mechanism under the condition of nonconflicting behaviors.*

Proof. One has

$$\frac{\partial e_1}{\partial \beta} = \kappa_1 > 0,$$
$$\frac{\partial e_2}{\partial \beta} = -\kappa_2 < 0, \qquad (15)$$
$$\frac{\partial e_2}{\partial (1-\beta)} = \kappa_2 > 0.$$

Proposition 2. *Under conditions with conflicting behaviors, the effort levels of the contractor and the owner are related to each other. Effort levels are also related to their own outcome coefficients of effort levels, and the contractual coefficient of benefit sharing (Figure 1). For the contractor, a high level of effort by the owner can motivate the contractor to also adopt a high level of effort. For the owner, a high level of effort by the contractor tends to decrease the owner's enthusiasm to adopt a high level of effort. Because of the coefficients of benefit sharing, and the ability for conflicts to be converted to benefits, the owner needs to provide a higher level of benefit sharing to motivate the contractor to adopt higher levels of effort. A high level of effort by the contractor, combined with a greater ability to convert conflicts to benefits, will lead to more benefits for the contractor. This increases the benefits for the contractor, but damages owner benefits, leading to a lower level of effort for the owner. Additionally, because of the coefficient of loss caused by conflicts, the contractor will balance benefit and loss when triggering conflicts. This leads the contractor to decide to adopt a high or low level of effort. As with the condition of nonconflicting behaviors, a high level of benefit sharing contributes to a high level of effort by the contractor, while leading to a lower level of effort by the owner.*

Proof. One has

$$e_1 = \mu e_2 + \beta\kappa_1 - \eta \quad \frac{\partial e_1}{\partial \beta} = \frac{\kappa_1 - \mu\kappa_2}{1+\mu^2} > 0$$
$$e_2 = -\mu e_1 + (1-\beta)\kappa_2 \quad \frac{\partial e_2}{\partial \beta} = -\frac{\kappa_2 + \mu\kappa_1}{1+\mu^2} < 0. \qquad (16)$$

Proposition 3. *Under the condition of conflicting behaviors, the contractor determines the effort level, by considering the benefit and loss caused by conflict behaviors. Generally, more losses caused by conflicts lead to lower levels of effort by the contractor. For the contractor, the benefits of converting conflicts relate to the owner's effort level; as such, the contractor will examine and weigh the ability of the benefit achieved by convert conflict behaviors to benefits. This determines the reasonable effort level. For the owner, a greater ability to convert conflicts for the benefit of the contractor and lower losses caused by conflicts lead to lower levels of effort by the owner. This reflects the fact that conflict behaviors have constructive or destructive effects on the benefits for the owner and contractor. Whether the contractor chooses to trigger conflicts or not depends on the absolute values of constructive or destructive effects. If triggering conflicts bring benefits to the contractor, the contractor will adopt conflict behaviors. If triggering conflicts cause losses to the contractor, the contractor will not adopt conflict behaviors. This prompts the owner to adopt effective bonus and penalty methods to decrease the loss caused by conflicts. The owner should observe information about effort levels, resource allocations, and benefit sharing by the contractor, and subsequently formulate an effective bonus and penalty mechanism.*

Proof. One has

$$\frac{\partial e_1^*}{\partial \mu} = \frac{(1-\mu^2)\kappa_2(1-\beta) - 2\mu(\kappa_1\beta - \eta)}{(1+\mu^2)^2} > 0 \quad \frac{\partial e_1^*}{\partial \eta} = -\frac{1}{1+\mu^2} < 0$$
$$\frac{\partial e_2^*}{\partial \mu} = -\frac{(1-\mu^2)(\kappa_1\beta - \eta) + 2\mu\kappa_2(1-\beta)}{(1+\mu^2)^2} < 0 \quad \frac{\partial e_2^*}{\partial \eta} = \frac{1}{1+\mu^2} > 0. \qquad (17)$$

Proposition 4. *Under the condition of conflicting behaviors, the coefficient of benefit sharing depends on the outcome ability of the owner and contractor and also depends on the coefficients of converting conflict behaviors to benefits and the loss caused by conflicts. Higher levels of converting conflict behaviors to benefits and lower losses caused by conflicts lead to a higher level of benefit sharing for the owner. This lowers the possibility that the contractor will adopt conflict behaviors. One potential explanation is that conflicts can not only benefit the owner but also simultaneously cause losses to the owner. If the contractor has a greater ability to convert conflicts to benefits, there are more losses for the owner. Thus, if the owner tends to avoid the loss caused by conflicts, the owner will strengthen contractor incentives. Additionally, when the contractor experiences higher losses caused by conflicts, there are more benefits converted from the conflict for the owner. If the owner's benefits can be forecasted, the owner will decrease contractor incentives to enhance its own benefits.*

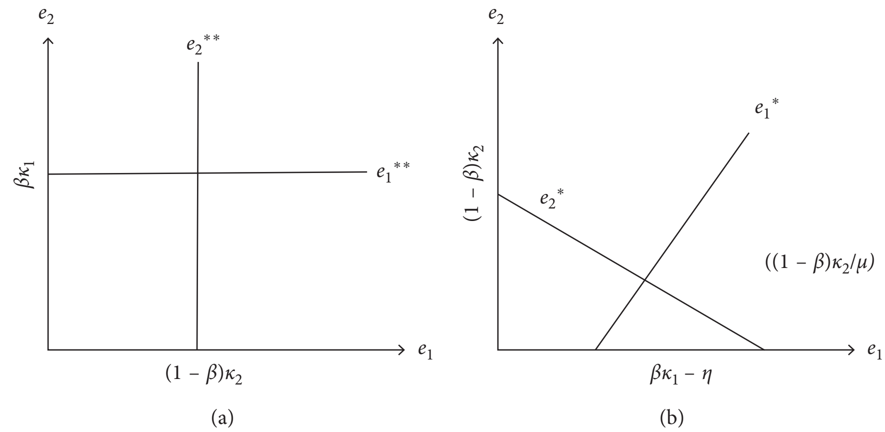

Figure 1: The effort levels of the owner and contractor under different conditions.

Proof. One has

$$\frac{\partial\beta^*}{\partial\eta}=-\frac{\kappa_1}{\kappa_1^2+\kappa_2^2+\rho(1+\mu^2)\sigma^2}<0$$
$$\frac{\partial\beta^*}{\partial\mu}=\frac{2\kappa_1\kappa_2[\kappa_1^2+\kappa_2^2+\rho(1+\mu^2)\sigma^2]-2\mu[\kappa_1^2+2\mu\kappa_1\kappa_2-\eta\kappa_1]}{[\kappa_1^2+\kappa_2^2+\rho(1+\mu^2)\sigma^2]^2}>\frac{2(\kappa_1\kappa_2-\mu)[\kappa_1^2+2\mu\kappa_1\kappa_2-\eta\kappa_1]}{[\kappa_1^2+\kappa_2^2+\rho(1+\mu^2)\sigma^2]^2}>0. \tag{18}$$

Proposition 5. *When a contractor triggers conflict, that conflict may not bring a greater benefit. This depends on the contractor's own characteristics, such as the outcome coefficient of effort, the ability to convert conflicts to benefits, and the effort level. It also depends on the effort level of the owner. The contractor triggering conflicts brings a better benefit only when $\eta<2\mu\kappa_2$. This indicates that the benefit from converting the conflicts is greater than the loss caused by the conflict. Under this situation, the contractor will trigger conflicts; otherwise, the contractor will not trigger conflicts. Thus, the contractor may enhance its own benefit by triggering conflicts. Consequently, the owner may increase its own benefit by adopting reasonable conflict management strategies. Therefore, if the owner can select reasonable conflict management strategies, it may create a better project benefit. This validates the hypothesis that conflicts may have a positive effect on project benefits.*

Proof. One has

$$\beta^{**}-\beta^*=\frac{\kappa_1^2}{\kappa_1^2+\kappa_2^2+\rho\sigma^2}-\frac{\kappa_1^2+2\mu\kappa_1\kappa_2-\eta\kappa_1}{\kappa_1^2+\kappa_2^2+\rho(1+\mu^2)\sigma^2}>\frac{\kappa_1\eta-2\mu\kappa_1\kappa_2}{\kappa_1^2+\kappa_2^2+\rho(1+\mu^2)\sigma^2}. \tag{19}$$

4.2. Model Simulations

4.2.1. Effects of Effort Levels of the Owner and Contractor on Project Benefits. Based on (3)–(5), (13), and (14), we set $\kappa_1=5$, $\kappa_2=4$, $\rho\sigma^2=20$, $\mu=0.6$, and $\eta=0.3$. We then simulate the effects of effort levels (e_1, e_2) on the project benefit (U), the contractor's net benefit (U_1), and the owner's net benefit (U_2). Figure 2 shows the results. Figure 2(a) shows that project benefits reach an optimal value only when the effort levels of the contractor and owner (e_1^*, e_2^*) achieve a stable and balanced state. This is consistent with the model analysis. Figures 2(b) and 2(c) show that the net benefits of the owner and contractor increase as the other parties' effort level is enhanced; the outcome of enhancing their own effort levels is represented by an inverted U curve. This reflects the fact that the contractor will decide whether to trigger conflicts, based on the owner's effort level. The owner will adjust its own strategy, based on the contractor's behavior. Thus, the effort levels of the contractor and owner affect each other, as well as their own net benefits. Additionally, for the owner and contractor, adjusting their own effort levels is critical to enhancing their own net benefits. However, increasing their own effort levels does not necessarily enhance their own net benefits. This depends on the other parties' effort level. Thus, the owner's optimal strategy is adjusting its strategy based on the contractor's behaviors.

4.2.2. Effects of Coefficients of Converting Conflicts to Benefits and the Loss Caused by Conflicts on Effort Levels. Based on (10), (11), (13), and (14), we set $\kappa_1=5$, $\kappa_2=4$, and $\rho\sigma^2=20$. We then simulate effects of coefficients of converting

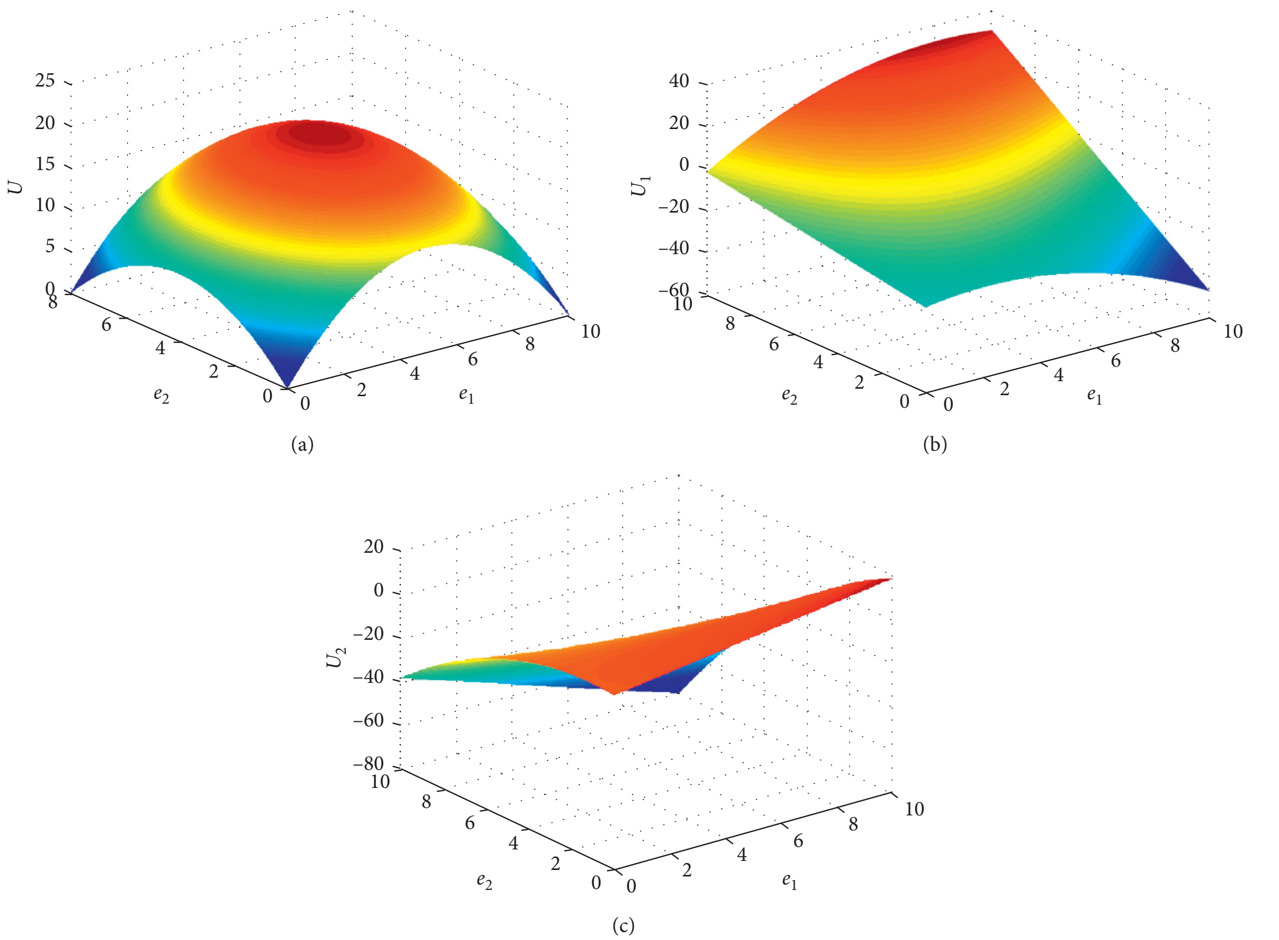

Figure 2: Effects of effort levels of the owner and contractor on project benefits. (a) Effects of e_1 and e_2 on U. (b) Effects of e_1 and e_2 on U_1. (c) Effects of e_1 and e_2 on U_2.

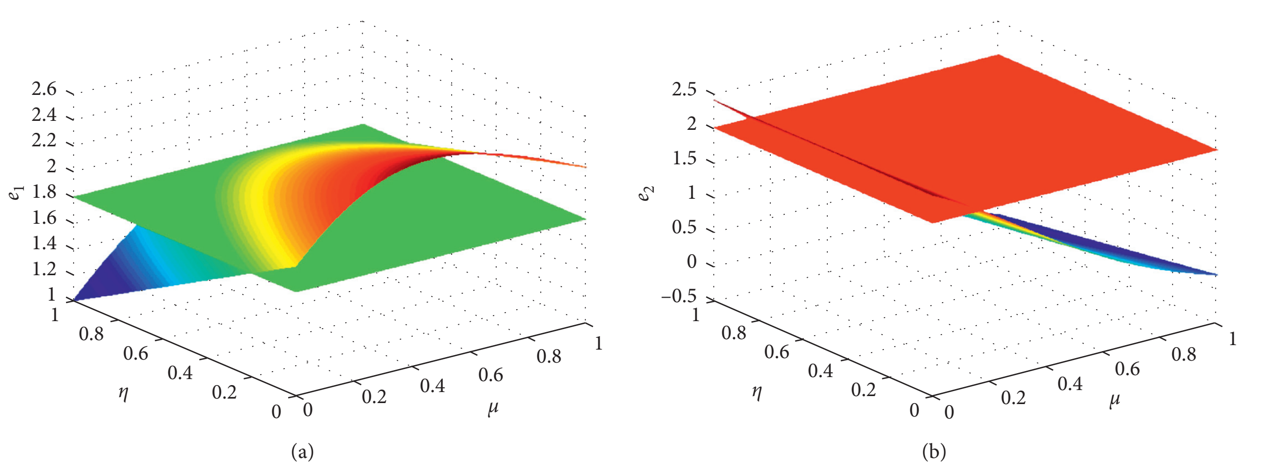

Figure 3: Effects of coefficients of converting conflicts to benefit and the loss caused by conflicts on effort levels. (a) Effects of μ and η on e_1. (b) Effects of μ and η on e_2.

conflicts to benefits (μ) and the loss caused by conflicts (η) on effort levels (e_1, e_2), under conflicting and nonconflicting conditions. Figure 3 shows the results, demonstrating that when there are conflict behaviors between the contractor and owner, higher levels of the coefficient of converting conflicts to benefit (μ) and lower levels of the coefficient of the loss caused by conflicts (η) contribute to higher levels of effort by the contractor. Lower levels of the coefficient of converting conflicts to benefits (μ) and higher levels of the coefficient of the loss caused by conflicts (η) contribute to

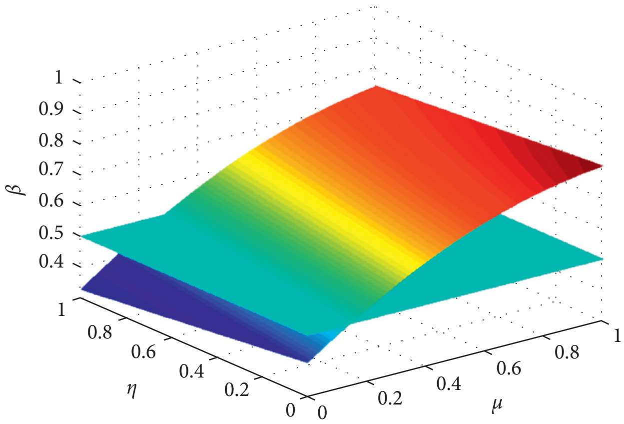

Figure 4: Effects of coefficients of converting conflicts to benefit and the loss caused by conflicts on the coefficient of benefit allocation.

higher levels of effort of the owner. This is consistent with Proposition 3. Compared with Figures 3(a) and 3(b), the effort levels of the contractor and owner under conflicting conditions may exceed their corresponding values under nonconflicting condition. This reflects the fact that if conflicts can bring more benefits for the owner and contractor, both may be willing to initiate conflict behaviors. This also means conflict behaviors may have a constructive effect on project benefits, which benefits the effort levels of the owner and contractor. The critical question is whether the constructive effect simultaneously affects the owner and contractor. In other words, it creates the question of whether there is a balanced point (μ^*, η^*) that maximizes values of (e_1, e_2). In fact, this situation may be achieved when considering the effects of different types of conflicts. The contractor should consider and control the relationship between the benefit and loss caused by conflict behaviors, adjusting their influence on the owner's effort level. Furthermore, the owner should adjust its strategy to respond to contractor behaviors. Under these conditions, conflict behaviors between the owner and contractor may be constructive and contribute to project benefits. This verifies the constructive aspect of conflict behaviors in construction projects.

4.2.3. Effects of Coefficients of Converting Conflicts to Benefit and the Loss Caused by Conflicts on the Coefficient of Benefit Allocation. Based on (11), (13), and (14), we set $\kappa_1 = 5$, $\kappa_2 = 4$, and $\rho\sigma^2 = 20$. We then simulate the effects of the coefficient of converting conflicts to benefit (μ), and the loss caused by conflicts (η) on the coefficient of benefit allocation (β), under conflicting and nonconflicting conditions. Figure 4 shows the results, demonstrating that conflict behaviors between the contractor and owner lead to higher levels of the coefficient of converting conflicts to benefit (μ) and lower levels of the coefficient of the loss caused by conflicts (η) contribute to a greater allocation of benefits to the contractor. This is consistent with Proposition 4. Compared with the nonconflicting condition, the coefficient of benefit allocation (β) may be higher or lower than the corresponding value with the variation of coefficients of converting conflicts to the benefit and loss caused by conflicts. This reflects the fact that triggering conflict behaviors would not always benefit the contractor; in fact, it may cause a loss for the contractor. Therefore, the contractor should balance coefficients of converting conflicts to benefit and the loss caused by conflicts and consider the owner's scoping strategy. This would lead the contractor to reasonably select its own behaviors and effort level, with a goal of increasing its own net benefit.

4.2.4. Effects of Coefficients of Converting Conflicts to Benefit and the Loss Caused by Conflicts on Project Benefits. Based on (3)–(8), we set $\kappa_1 = 5$, $\kappa_2 = 4$, $\rho\sigma^2 = 20$, $\mu = 0.6$, and $\eta = 0.3$. Then, we simulate the effects of the coefficients of converting conflicts to benefits (μ) and the loss caused by conflicts (η) on the project benefit (U), the contractor's net benefit (U_1), and the owner's net benefit (U_2) under conflicting and nonconflicting conditions. Figure 5 shows the results and demonstrates that lower levels of the coefficient of converting conflicts to benefit (μ) and lower levels of the coefficient of the loss caused by conflicts (η) contribute to greater project benefits. Higher levels of the coefficient of converting conflicts to benefit (μ) and lower levels of the coefficient of the loss caused by conflicts (η) contribute to greater net benefits for the contractor. Lower levels of the coefficient of converting conflicts to benefit (μ) and higher levels of the coefficient of the loss caused by conflicts (η) contribute to greater net benefits for the owner. Compared with Figures 5(b) and 5(c), the net benefit of the contractor is reflected in an inverted U shape, with the variation of the coefficient of converting conflicts to benefit (μ), the owner's net benefit is represented by an inverted U shape with the variation of the coefficient of the loss caused by conflicts (η). This indicates that if the owner can design a reasonable conflict management mechanism, the contractor can balance the relationship between the benefit and loss caused by conflict behaviors. Under this situation, the destructive effect of conflicts can be avoided, and the constructive effect of conflicts can be introduced. Additionally, compared with Figures 5(a)–5(c), conflict behaviors between the owner and contractor appear to have constructive effects on project benefits, thus strengthening the net benefits for the owner and contractor.

4.2.5. Numerical Example. In this section, different situations of outcome coefficients of the owner and contractor are addressed to compare the model results. In addition, different situations of the coefficients of converting conflicts to benefit (μ) and the loss caused by conflicts (η) under the same outcome coefficients of the owner and contractor are calculated. Applying the conflict decision model with owner and contractor parameter values allows the calculation of effort levels of the owner and contractor, the net benefits for the owner and contractor, the benefit allocation coefficient,

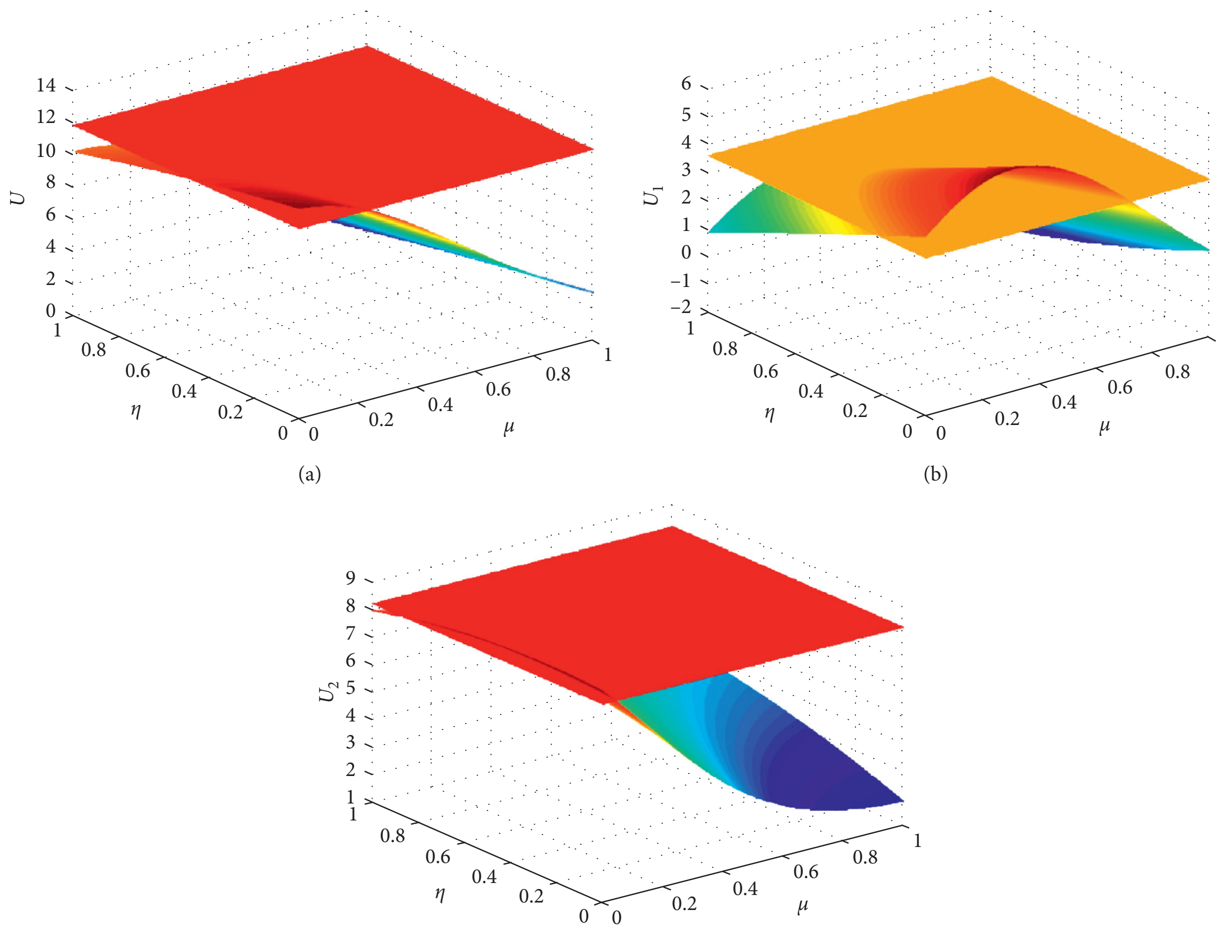

FIGURE 5: Effects of coefficients of converting conflicts to benefit and the loss caused by conflicts on benefits. (a) Effects of μ and η on U. (b) Effects of μ and η on U_1. (c) Effects of μ and η on U_2.

TABLE 1: The results of conflict decision model between the owner and contractor under different situations.

		(e_1, e_2)	β	U_1	U_2	U
$\kappa_1 = 5, \kappa_2 = 4$	$\mu = 0, \eta = 0$	(2.05, 2.36)	0.41	4.29	8.83	13.12
	$\mu = 0.1, \eta = 0.9$	(1.69, 1.91)	0.48	2.80	7.75	10.55
	$\mu = 0.3, \eta = 0.3$	(3.21, 0.30)	0.68	6.08	1.29	7.37
	$\mu = 0.3, \eta = 0.6$	(2.83, 0.53)	0.66	1.11	6.73	7.84
	$\mu = 0.6, \eta = 0.3$	(3.20, −1.40)	0.86	4.03	−7.31	−3.28
	$\mu = 0.9, \eta = 0.1$	(3.72, −2.54)	0.96	3.19	−17.19	−14.00
$\kappa_1 = 4, \kappa_2 = 4$	$\mu = 0, \eta = 0$	(1.23, 2.77)	0.31	3.22	7.24	10.46
	$\mu = 0.1, \eta = 0.9$	(0.83, 2.44)	0.37	2.57	5.79	8.36
	$\mu = 0.3, \eta = 0.3$	(2.29, 1.04)	0.57	1.74	5.17	6.91
	$\mu = 0.3, \eta = 0.6$	(1.94, 1.25)	0.54	1.67	5.51	7.18
	$\mu = 0.6, \eta = 0.3$	(2.13, 0.44)	0.74	3.93	3.28	7.21
	$\mu = 0.9, \eta = 0.1$	(2.42, −1.47)	0.89	1.76	0.25	2.01
$\kappa_1 = 4, \kappa_2 = 5$	$\mu = 0, \eta = 0$	(1.05, 3.69)	0.27	4.70	9.90	14.60
	$\mu = 0.1, \eta = 0.9$	(0.71, 3.32)	0.32	4.56	8.11	12.67
	$\mu = 0.3, \eta = 0.3$	(2.28, 1.73)	0.52	4.42	6.61	11.03
	$\mu = 0.3, \eta = 0.6$	(1.96, 1.95)	0.49	4.28	7.04	11.32
	$\mu = 0.6, \eta = 0.3$	(2.51, 1.34)	0.71	6.65	2.12	8.77
	$\mu = 0.9, \eta = 0.1$	(2.89, 0.58)	0.80	2.06	1.22	3.28

and the project benefits under different situations. Table 1 shows the results.

5. Conclusions and Implications

This study considered the effects of conflict behaviors on project benefits. Based on the inherent nature of construction projects, this study constructed a decision model between the owner and contractor's conflict behaviors, then analyzed the model under conflicting and nonconflicting conditions. A simulation and numerical example were implemented to verify the conclusions from the model analysis. The study led to four key results. First, effort levels for the contractor and owner only relate to coefficients of benefit sharing and effort outcomes under nonconflicting condition. Effort levels also relate to the coefficients for converting conflicts to benefits and the loss caused by conflicts under conflicting condition. Second, higher levels of the coefficients for converting conflicts to benefits and lower levels of the coefficient of the loss caused by conflicts contribute to a higher level of net benefits for the contractor and a lower level of net benefits for the owner. Third, this study verified the constructive effect of conflict behaviors between the owner and contractor; conflict behaviors may have constructive effects on the project benefits. This can strengthen the net benefits for the owner and contractor. Fourth, if the owner can design a reasonable conflict management mechanism, the contractor can balance and control the benefit and loss caused by conflicts. This has the benefit of strengthening the effort levels for the owner and contractor, improving project benefits.

Due to complementary core abilities and consistency in the willingness to cooperate, conflict behaviors between the owner and contractor in construction projects are cooperative-based conflicts. As such, conflicts may have constructive effects on project benefits. The conclusions of this study highlight three key implications for project management. First, the coefficient of benefit allocation depends on two factors: contractor-related factors, such as the coefficient of effort outcome, converting conflicts to benefits; and project-related factors, such as the project's external uncertainty. Facing a complex external project environment makes it difficult for the owner to evaluate the effort level of the contractor; as such, the owner may adopt a weak incentive intensity. Second, balancing the benefit and loss caused by conflict behaviors can lead to a more reasonable risk allocation between the owner and contractor [35]. This can prompt the owner and contractor to enhance their own effort levels, achieving improvements in benefits. Third, the owner should construct a fair and reasonable benefit-sharing mechanism and optimize the level of resource input and allocation between the owner and contractor. This builds a trust relationship between the owner and contractor, thus avoiding the destructive effects of conflicts and promoting constructive effects.

Few studies have emphasized effects of conflict on construction project benefits. This study constructed a decision model using game theory to bridge this gap. This study contributes significant theoretical and practical insights to manage conflicts in construction projects. However, an evaluation of the proposed model and conclusions must also consider the study's limitations. First, the proposed model considers the interorganizational relationship between the owner and contractor, while the conflict relationship may involve more stakeholders. Second, this study did not address different types of conflicts that may also affect benefits. In project practice, contractor's commitment may change as the project life cycle evolves, and the influence of conflicts on project benefits may change. These limitations highlight future research directions. In conclusion, this study contributes to the existing knowledge by proposing and validating a game-based decision model that project managers can use to address conflicts in construction projects. The model highlights practical implications, providing a clear understanding of effects of conflict on benefits in construction projects. The study also provides a theoretical reference for properly managing conflicts among stakeholders and realizing overall project benefits.

Data Availability

The data of this research is available on the request to the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Article

A Parameter Classification System for Nonrevenue Water Management in Water Distribution Networks

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Nonrevenue water (NRW) in a water distribution network is the water lost from unbilled authorized consumption, apparent losses, and real losses compared to the total system input volume. Nonrevenue water is an important parameter for prioritizing water distribution network improvement intervention planning, and it is necessary to identify the affecting parameters. A factor classification system has been developed based on the factors suggested by major institutions and researchers to propose an effective NRW classification system in a water distribution network. The factor classifications used include physical, operational, and socioeconomic factors that could affect NRW. Appropriate standards are required when classifying water main parameters. In this study, three criteria were proposed to create independent factors. The first relates to the properties of the parameter. One determines whether the parameters related to the water network are more suitable for physical, operational, or socioeconomic factors and classifies them into one of these three parameters. Second, one considers data availability and data characteristics taking into account the scope of the coverage area. Third, it must be possible to quantify selected parameter data. Whether the collected data are numerically valid and whether it can be used as a standard for assessment or comparison between regions must be examined. The quantification portion of the qualitative data in managing NRW is important and needs to be used in accordance with reasonable standards. In this study, more factors can be used depending on those selected, and it was found that NRW prediction that reflects regional characteristics is possible.

1. Introduction

Climate change and population growth have resulted in large requirements of water in domestic, industrial, and agricultural purposes. Water distribution networks are subject to deterioration over time, and this usually leads to difficulties such as decreased capacity of hydraulic facilities, increased volume of water loss, service disruption, and lower water quality. Additionally, the continuing increase in consumer water demand presents additional problems such as low pressure in a pipe network. Migration to urban areas and rapidly growing populations in developing countries has resulted in a vital need for the construction of adequate water systems to distribute water to residents [1–4].

During the early 1990s, no standard term existed to express and evaluate water losses in a water supply system. The International Water Association (IWA) has recognized this problem and established the Water Loss Task Force (WLTF). The WLTF has examined international best practices and developed a standardized terminology for nonrevenue water (NRW) [5, 6].

Nonrevenue water (NRW) is one of the major issues water utilities are facing today, especially in areas with severe water scarcity conditions [7, 8]. NRW includes physical (pipe leaks) and commercial losses (unbilled metered water, unmetered public use, illegal connections, meter error, and water for which payment is not collected) [9, 10]. The IWA has proposed performance indicators [11–14]. In addition, it has been suggested to avoid the use of a percentage indicator in performance comparison, especially in target areas where there are large differences in consumption per service connection [15, 16].

Based on an analysis of the influence of pipe damage on the overall pipe distribution network in determining priorities for improving a water pipeline [17], a systematic replacement and remediation plan has been developed for the maintenance of the metropolitan waterworks [18]. Although projects to improve old waterworks are being continuously implemented, it is difficult to avoid economic losses and improve a system's function by enhancing the assessment and accident prevention of old pipes that depend on empirically based judgments [19].

Therefore, advanced study and analysis are required of the factors affecting leaks in decision making to prioritize maintenance of water distribution systems, as well as to identify the physical and operational factors affecting NRW with parameters such as leaks, hydraulic pressure, water quality, and water demand volume [8]. To reduce the NRW, studies analyzing pipe networks, increasing reliability, diagnosing pipe network technology, and evaluating pipe deterioration have been conducted to promote an optimal water distribution system [20–22].

Leak analysis is possible by examining each factor affecting a water distribution system. Yet a water network in a large city is complex and comprises various parameters. To estimate the leak volume, the main water supply network parameters appropriate for the regional characteristics are selected, and an NRW calculation model, developed by statistical methods, will play an important role in operating and managing a water supply network [4].

The NRW index of a water distribution system needs to be proven via relationship with the characteristics of the district metered area and quantifying the influence of related parameters. In districts with severely deteriorated pipe networks, for example, the NRW can be considered high because of many leaks but their extent is not quantified. Unless the correlation between regional characteristics and the NRW is properly identified, NRW management might prove unrealistic and uneconomic even if its ratio is high due to local specificity [4].

Korea's NRW is considered a management performance index of water distribution systems of waterworks operators and municipalities. It can be considered the economic feasibility of a project, suitability of the operational management, and efficiency of investment. A high NRW in terms of economic significance means that the recovery rate compared to the production cost is low [23].

A reduction in NRW is thus essential to maintain sound financial operation of a waterworks business. In operational management, a low NRW ratio indicates appropriate management in water distribution systems; a high NRW usually means problems in operational management of the facility (unmeasured quantities using water meters, leaks, and illegal use).

In addition, investment and expansion of water supply facilities requires a huge budget and determination on appropriate expectation face constraints. Making a decision is difficult on what to prioritize when improving facilities and operations comparing and analyzing the lack of supplied water with the volume of lost tap water. In this case, NRW is expected at driving the project by determining whether to improve or expand the facility's water supply operation. The existing NRW method is based on observational data. Management of leakage is difficult; thus, an analysis of influencing parameters can calculate NRW.

In this study, a classification system for NRW management was suggested using survey results of researchers and international institutions via an analysis of the main parameters of water distribution systems. This study identified parameters for NRW management in water distribution systems. The main content of the research is summarized as follows.

First, a literature survey was conducted using data from domestic and foreign researchers. The relationship of parameters in a water distribution system and NRW, a statistical approach, and ANN studies were reviewed.

Second, a study of parameters related to water distribution systems was conducted. The physical, operational, and socioeconomic factors of water distribution systems were identified and then classified using detailed characteristics for application to NRW management.

Third, a parameter classification process with appropriate standardization was developed avoiding duplication of each parameter's characteristics.

The factor classification system is presented using the aforementioned three steps. The factor classification table was created considering additional quantification such that it can be used for management and estimation of NRW.

2. Definition of NRW in Water Distribution Systems

NRW is water that has been produced and is "lost" before it reaches the customer. Losses can be real losses (e.g., via leaks, sometimes also referred to as physical losses) or apparent losses (e.g., via theft or metering inaccuracies) [24–26]. NRW corresponds to water loss due to leaks, commercial problems, and nonbilled consumption such as a lack of water meter precision or mistakes in client databases. In (1), A_p is the volume of water produced per unit time and A_b is the volume of billed water per unit time [1]:

$$\text{NRW ratio} = \frac{A_p - A_b}{A_p}\,(\%). \tag{1}$$

The definition of NRW is described as the difference between the volume of water input into a water distribution network and the volume billed to customers. NRW has three components as follows [1].

Physical losses comprised of leaks from all parts of the distribution network and overflows at the facility's storage tanks. They can be caused by poor operations and maintenance, a lack of active leak prevention, and poor quality underground assets. Commercial losses are caused by under registration of water meters, errors in data treatment, and the theft of water in various forms.

Unbilled and authorized consumption contains water used for operational purposes or firefighting which is provided free of charge to select consumer groups. Various indicators measure NRW, and essentially all have weaknesses. The generally used indicator is NRW defined as a percentage of water provided.

Table 1: Components of water balance [14, 15, 29].

System input volume	Authorized consumption	Billed authorized consumption	Billed metered consumption (including water exported)	Revenue water
			Billed nonmetered consumption	
		Unbilled authorized consumption	Unbilled metered consumption	Nonrevenue water
			Unbilled nonmetered consumption	
	Water losses	Apparent losses	Unauthorized consumption	
			Metering inaccuracies	
		Real losses	Leaks in transmission and/or distribution mains	
			Leaks and overflows at a utility's storage tanks	
			Leaks in service connections to customer meters	

The IWA recommends the use of alternative indices such as water losses per junction and per main length and infrastructure leakage indices [11–13, 24–27]. The latter is a complex index as it also measures pressure in the DMA of water distribution network.

Collecting pressure data at junction for a utility is complicated, however, as measured pressure can vary widely within a piped water supply system. It is thus useful as an index when improving the system performance but cannot be easily used to evaluate network losses between utilities, as averaging such an index for a utility might fail to provide useful data except to reflect an underlying problem [28].

As parameters of water balance in Korea and their definitions are different from those of the IWA, they were rearranged as shown in Table 1 [14, 15, 29]. Metering and under registration were recalculated, and the remaining amount of the recalculation was added to the ineffective water, which was considered equivalent to the real losses of the IWA's water balance. Water theft and illegal connections are apparent losses of NRW.

Because of the various definitions and deficiency of well-documented procedures for several parameters (e.g., public use, supplier's official use, and metering under registration), selected data could be inaccurate. Mean pressure and location of water meters were estimated using limited samples, possibly causing data variation [29].

This study focused on physical and operational parameters related to water distribution systems. Physical parameters were considered, and measured data such as the number of leaks were also used for NRW management. Components of water balance in water distribution systems are shown in Table 1 as presented by the IWA [14, 15, 29].

The combined water balance in a network can be calculated using real measured data but doing so in a real water distribution system can be difficult because of the unconstructed district metered area (DMA) and design errors in the water distribution system. In addition, periodic management is an essential element in water distribution systems including identification of leaky pipes, hydraulic pressure management, and proper pump operation.

Because Korea has a detailed standard for its volume of water, NRW calculation using more diverse parameters is necessary. Under the conventional NRW calculation, consideration of physical parameters is needed more than socioeconomic parameters. If physical parameters are only used to calculate NRW, it could reduce the economic cost of measuring NRW and help in selecting the maintenance of DMAs in water distribution systems.

3. Development of Parameter Classification System

3.1. Previous Research of Parameter Classification in Water Distribution Systems. In previous research of the main parameters for NRW management, Shinde et al. suggested reliable indicators for waterworks and stable management in water supply systems [7]. Performance indicators (PIs) and quantifiable data (reflecting operational indicators in the water distribution network) were used as indicators related to those used in NRW management. The purpose of PIs is not only to perform statistical analysis but also to provide efficient information to support in decision making. PIs of international organizations are presented in Table 2 [7, 8].

As seen in Table 2, international organizations have recommended similar items. The apparent differences shown in Table 2 are due to the various DMAs for which the indicator system was developed. For example, the World Health Organization (WHO) indicator is suitable for developing countries and districts where costs and services are inadequate.

The IWA components, on the other hand, cover a wide range of indicators to assess every aspect of the system across topographical boundaries and are considered major reference sources in the global water industry [30]. Recent studies have increasingly focused on sustainability indicators [31–34] and those that integrate social and economic aspects of waterworks to ensure long-term service [8, 9].

In Table 2, the PIs presented by the IWA include physical and operational factors used in the management of NRW and other water resource, and personal, service quality, and economic and financial indicators were suggested.

For water resources, the efficiency of a water supply can be evaluated by water quality, distance from the water source, and scale of water supply facilities. In terms of quality of service, indicators should be included, but depending on the service system and the water supply facilities such as the reservoir, pressurization facility, water purification plant, and valve facility, a major influence on the manual supply system is observed. This is an essential factor in water loss when managing NRW.

Economic and financial indicators can affect NRW including the tax and water rate system according to the living criteria of residents in the water supply area, and the reconstruction budget of water supply facilities. Thus, this index is also directly related to NRW.

In addition to the aforementioned IWA indicators, the main indicators suggested by the other organizations are

Table 2: PI themes recommended by international organizations [7, 8].

IWA (2006)	IBNET (2005)	WHO (2000)	WB (1999)
(i) Water resources (ii) Personnel (iii) Physical (iv) Operational (v) Quality of service (vi) Economic and financial	(i) Service coverage (ii) Water consumption and production (iii) NRW (iv) Metering practices (v) Pipe network performance (vi) Cost and staffing (vii) Quality of service (viii) Billing and collection (ix) Financial performance (x) Assets (xi) Affordability (xii) Process indicators	(i) User satisfaction (ii) Community management (iii) Financial (iv) Level of service (v) Materials (vi) Personnel (vii) Equipment (viii) Work control	(i) Coverage (ii) Water consumption and production (iii) Water unaccounted for (iv) Metering practices (v) Pipe network performance (vi) Cost and staffing (vii) Quality of service (viii) Billing and collection (ix) Financial performance (x) Capital investment

reviewed. NRW is included as an indicator from the International Benchmarking Network for Water and Sanitation Utilities (IBNET) including service convergence, metering practices, cost and staffing, quality of service, and assets. These are more detailed than the IWA indicators and easier for the user to understand.

WHO has provided indices that take account into customer level rather than user satisfaction and community management. The World Bank provides economic and financial indicators with a weighting factor such as those of water production, water consumption, and water unaccounted for; billing and collection; and capital investment.

The fundamental concept of NRW comprises real (quantity of leaks) or apparent losses (inaccurate metering and illegal use). These losses are direct physical losses, and their management is needed to accurately measure water using meters installed in water distribution systems.

When approximating the technical circumstance of water distribution networks, a qualified analysis of the network's individual components (e.g., separate water pipelines, pressure zones, or measurement districts) is conducted using physical indicators. In terms of the scope and availability of the required supporting analysis, the following physical and operational indicators are recommended [35]:

(a) *Pipe age*. The service life of a pipe depends on many factors. For each pipe material in the evaluated portion of a water distribution network (pressure zone and water pipeline), consideration of the DMA region in operational experience, as well as an assessment of the theoretical service life of the pipe materials and a comparison to the structure and age of the operated network, is needed. This study chooses the deteriorated pipe ratio for the pipe age indicator. In addition, each DMA network's calculated age of pipes, and its ratio of network data were considered.

(b) *Failure fate*. Failure evaluation is an important factor for the operational maintenance, repair, and reconstruction planning of a water distribution network. The main indicator for failure analysis in terms of the needs of an evaluated technical circumstance is the failure rate expressed as a number of failures related to the pipe length and unit of time (usually the number of failures per km per year) and the dynamics of failures. This study suggests the number of leaks as the main parameter [35, 36].

(c) *Water losses*. A number of factors are used to evaluate the water losses, but not all include the effect of a network's technical condition. For estimating the technical condition of a water distribution network, recommended indicators include the unit leakage, infrastructure leakage index (ILI), and economic leakage index (ELI). This study considered water losses using the number of leaks in each DMA.

(d) *Pressure in pipe network*. From the perspective of the effect of operational pressure on the network's technical condition, a general observation is that a high value of operating pressure is undesirable. Even less desirable is rapid deviation in hydrodynamic pressure each day. The operating pressure value also affects other indicators for evaluating the network's technical condition: water losses, failure rate, and theoretical service life of the pipe material. Water losses caused by leakage, pipe failure, and higher pipe hydraulic pressure can affect energy demands at each junction of a water distribution network. Thus, energy demand is an important parameter explaining the hydraulic pressure of a water distribution system [4, 38].

(e) *Reliability*. Using qualitative and quantitative reliability factors allows identification of the network's critical facilities and their prioritization in reconstruction planning. For each indicator, it is possible to define the processes for its determination, physical dimension, and method of presentation. Each indicator is also a means of monitoring the technical condition of the evaluated distribution network.

In Korea, the Ministry of Environment (MOE) has established the country's main indicators and the classification of water distribution systems. In the assessment of aging and DMAs, factors are classified based on the physical parameters of a water distribution network, and scoring is completed according to weights. According to the Water

Table 3: MOE's evaluation index for deteriorated pipes.

Indirect evaluation (10 items, 100 points)		Direct evaluation (12 items, 100 points)	
Pipe type (15)	Soil type (7)	Pipe diameter (27.3)	Thickness of sediment (14.9)
Pipe diameter (3)	Surrounding road (3)	Pipe thickness (12.4)	Pipe internal corrosion depth (3.4)
Inner pipe coating type (12)	Connection method (5)	Coating thickness (8.5)	Internal corrosion circumference (3.2)
Outer pipe coating type (4)	Number of leaks (7)	Pipe external corrosion depth (3.2)	Internal coating management (7.6)
Elapsed years (37)	Water quality (7)	External corrosion circumference (2.8)	Thickness of scale (7.3)
		External surface coating anagement (4.4)	Hydraulic pressure (5.0)

Source: Waterworks Network Diagnosis Manual [39].

Table 4: Classification of main parameters in water distribution systems [4, 8, 36–38].

Provider	Purpose	Parameter
Waterworks Network Diagnosis Manual (2007, Ministry of Environment) [38]	Water supply pipe (property data), deteriorated ratio	Pipe material, pipe type, inner and outer pipe coating types, elapsed years, soil type, number of complaints of leaks and water quality, pipe diameter, thickness and external corrosion depth, external corrosion circumference, thickness of scale, and others
	Evaluation of small DMA	Size configuration (loop or resin type), internal and external stagnation parts of DMA, occurrence of rust, scale attachment of pipe, hydraulic pressure and measurement facility in DMA, leak measurement management, and number of leaks
Park, IWA [23]	Leak evaluation index	Fiscal self-reliance ratio, reservoir capacity, water supply population, water price cost recovery rates, water meter (13 mm) installation rate, amount of daily water supply per person, and length of deteriorated (more than 20 years) and water supply pipe
	Effective parameter of revenue water ratio	Scale of water supply (population growth rate, population of water supply per number of demand junctions, and water supply rate), facility scale (total pipe length of DMA, administrative area, number and capacity of reservoirs, and water meter (13 mm) installation rate), financial condition (fiscal self-reliance ratio, investment ratios of maintenance cost compared to expenditures and facility improvement cost compared to expenditures, replacement rate of DMA pipes per year, and water price cost recovery rates), and deteriorated facility (length of deteriorated pipe, new installation per year, and number of leaks per number of demand junctions)
Jang [40]	Effective parameter of revenue water ratio	Number of leaks and demand junctions, pipe age, hydraulic pressure, and nightly minimum flow
Lee [41]	Rise in revenue water ratio	Replacement rates of DMA, inlet pipe and water meter, and recovery rate of leaks
Chung et al. [42]	Effective parameter of revenue water ratio	Population per pipe length in DMA, percentage of homes older than 21 years, ratio of apartment units, and installation rate of 13 mm for water meter

Supply Network Diagnosis Manual [39], the index of the deteriorated pipe is as shown in Table 3.

To assess the deterioration of a pipe, distinguishing indirect evaluation items is possible considering design parameters and numerical data and direct assessment items from measured values via pipeline inspection. Indirect assessment includes physical property elements such as pipe diameter, type, and external observation components such as the number of complaints regarding leaks and water quality.

Direct evaluation objects include pipe data such as pipe thickness, corrosion status, and sediment thickness in the pipeline and hydraulic pressure data generated from the distribution network. The assessment index of the deteriorated pipe ratio is composed of the physical components of pipelines and includes operational components such as hydraulic pressure, which is an appropriate classification system for examining a water distribution system.

Table 4 lists a classification of the parameters in a water distribution system as proposed by the MOE and major domestic studies.

3.2. Establishment of a Parameter Classification System. Adequate standards are mandatory when classifying the parameters of a water distribution network selected from among organizations and researchers. In this study, three criteria were proposed to create independent factors.

The factor classification system was based on the inherent properties of parameters. This study suggested if the parameters related to the water distribution network were more suitable for physical, operational, or socioeconomic parameters and classified them into one of these three groups.

The scope of coverage, data availability, and data characteristics were considered. When data were acquired, regional characteristics could be identified according to whether the boundary data were divided into administrations or DMAs.

Quantification of the data for the selection parameters was possible. Whether the collected data were numerically valid and could be used as a standard for comparison or assessment of regions was examined. If the designated

Table 5: Classification of effective parameters suggested for NRW management [4, 8, 36–38].

Primary	Secondary		Tertiary
Physical parameters	Pipe property	Pipe material, type, inner or outer coating type, elapsed years, mean pipe diameter, pipe thickness, length of water supply pipe, and metal pipe ratio	Pipe material, mean pipe diameter, length of water supply pipe, and elapsed years
	Water supply scale	Amount of daily water supply per person, water supply rate, number of demand junctions, and reservoir capacity per pipe length of water distribution systems	Amount of water supply per number of demand junctions
	Facility scale	Reservoir capacity, size, configuration (loop or resin type) and pipe length of DMA, area of administrative district, and number of reservoirs	Size and configuration (loop or resin type) and pipe length of DMA
	Facility deterioration	Evaluation, ratio and length of deteriorated pipe (age older than 20 years), external corrosion depth and circumference of pipe, internal corrosion depth of pipe and circumference, and new pipe installation per year	Ratio and evaluation of deteriorated pipe
	Others	Soil type (chemical classification)	*Included in evaluation of deteriorated pipe
Operational parameters	Leaks	Leak measurement facility in DMA and management, number of leaks (10 km), nightly minimum flow, and leak recovery rate	Number of leaks (10 km)
	Hydraulic pressure	Hydraulic pressure and stagnant part of DMA	Demand energy ratio
	Others	Number of complaints over water quality, self-production rate of tap water, replacement rates of inlet and DMA pipe, water meter and water distribution pipe per year, and installation rate of 13 mm water meter	*Included in evaluation of deteriorated pipe
Socioeconomic parameters	Population	Population of water supply per pipe length of water distribution systems, population growth rate, population of water supply per number of demand junctions	Population of water supply per number of demand junctions and population growth rate
	Financial condition	Fiscal self-reliance ratio, water price cost recovery rates, and investment ratio of maintenance cost compared to expenditures and that of facility improvement cost compared to expenditures	Fiscal self-reliance ratio and water price cost recovery rates
	Others	Percentage of homes older than 21 years and ratio of apartment units	—
Other parameters	—	User satisfaction	—

parameters express only qualitative characteristics that cannot be quantified, using them in NRW management is difficult.

The parameter classification system is objectively developed according to the characteristics of each parameter, and this made it possible to consider all the parameters of water distribution networks previously suggested by think tanks and researchers. Parameters related to NRW are examined in regard to physical, operational, and socioeconomic parameters. The effective parameters to NRW are selected according to the developed classification system of main parameters.

Based on these three standards for classification, NRW affecting parameters are classified as listed in Table 5 by using three classifications with no integration or redundancy.

3.3. Parameter Classification per Data Quantification. Figure 1 shows selected parameters from Table 5 further considering effective NRW parameters from international studies. As shown in Figure 1, the representative parameters for NRW management can be classified as either direct or indirect factors.

Direct factors are physical and operational parameters, and indirect factors are socioeconomic parameters and others. Classification between quantitative and qualitative parameters was also based on data collection considering the data characteristics of selected parameters. Quantitative parameters must be converted by using data quantification standards for each DMA or country.

3.3.1. Direct Factors. Physical factors such as mean pipe diameter, pipe length, number of demand junctions, pipe length per demand junction, amount of water supply per demand junction, and deteriorated pipe ratio have been used in previous studies. If used for NRW management, then the amount of water supply and deteriorated pipe ratio were chosen.

To apply physical parameters to the test bed, a pipe material can be selected an additional parameter as it can affect pipe breakage, pipe leaking, and rehabilitation that will influence the prediction results. Selection of data is necessary such that rehabilitation can be connected to the deteriorated pipe ratio.

Pipe materials such as cast iron and polyvinyl chloride (PVC) can affect the shape and scale in the pipe. Thus, when using a pipe material, a typical classification of the pipe material is required. In a general distribution network system, however, iron pipes such as cast iron or steel pipes are often used, so their use as categorized components can prove difficult depending on the region.

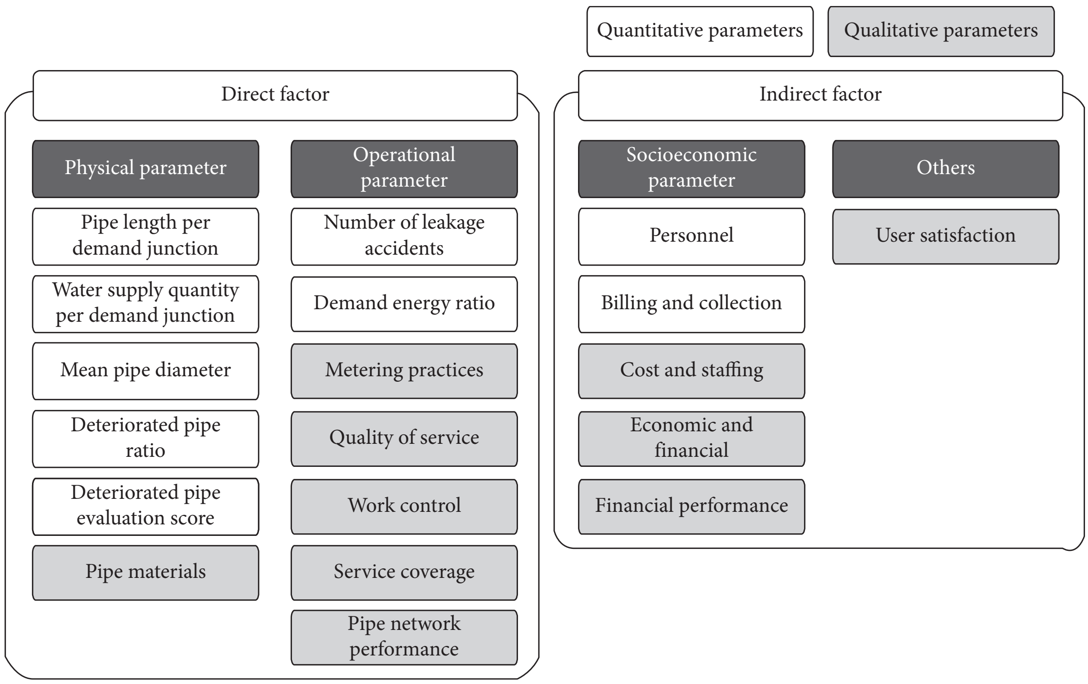

Figure 1: Classification of leading parameters for NRW management [4].

Among the direct factors, data on the number of leaks are collected through complaints from residents, thus obtaining reliable data for a specific area can be difficult. The demand energy ratio is a parameter that represents the hydraulic pressure of water distribution networks. It is closely associated with the number of leaks; if high hydraulic pressure is maintained in a water distribution network, the number of leaks will be increased.

The quality of water service, work control, metering practices, service coverage, and pipe network performance are PI factors serving as operational parameters. The quality of service indicates whether the entire procedure of water supply is systematically well established, such as if the water supply system is worked well or the frequency of accidents is low. These conditions can also contain the operation of physical factors such as valve-operating settings, pressurization facilities, optimal maintenance of residual chlorine, and prevention of water quality problems.

When calculating NRW, stable water supply assures water quality, but measures are required when water quality is difficult to maintain. One proposal seeks to preserve residual chlorine concentration by reducing the residence time in the pipeline in which residual chlorine concentration is not maintained compared to regional water-quality criteria.

In urban areas, water quality is not included as a parameter because of the short residence time, but rehabilitation time is longer in a rural area because pipe lengths for water supply are relatively long and the demand is lower than that in an urban area; rural areas are particularly sensitive to water quality parameters such as residual chlorine concentration. In that case, service quality considering water quality parameters can affect NRW.

Metering practice means periodic measurement and accuracy of water meters. Water meter provides physical measurements, but the measured data differ by the type of water meter.

Given its economic efficiency, a mechanical water meter is the most commonly used in Korea. Water meters include dry and wet types. Recently, digital ultrasonic water meters used to improve accuracy but are more costly than analog types and can have power supply problems.

If the parameters of water meter accuracy, periodic measurement, and demand analysis are combined, investigation of NRW characteristics of a target area might become more advantageous. Another crucial task is managing measurement data such that the values measured via a water meter are transformed into a database and a detail analysis can follow.

The factors of work control, pipe network performance, and service coverage are related to the necessary conditions to ensure that the hydraulic pressure in a water network is properly regulated to provide a stable water supply.

Water supply system's managers and operators can moderate the occurrence of leaks by improving the operation of the pipe network. For example, if the hydraulic pressure is high at a junction, the volume of leaked water in the water distribution network increases due to the pressure energy, which leads to a higher NRW.

To maintain an optimal junction pressure, optimal valve operation in the water distribution network and that of the pressurization facility can lower the NRW. Thus, the waterworks operator needs to establish an optimal operating system based on real measurement data. Service coverage varies between densely populated urban areas and rural areas. The network operator must devise an operating plan in which the area of the DMA system should be installed to maintain optimal supply pressure.

Developed artificial neural network (ANN) and multiple regression analysis models based on data of an area where a DMA system has been built can be utilized under a condition in which physical and operational element data are collected. Physical parameters are the components that have the greatest influence on distribution network design. Water service convergence is a key element in establishing and operating a network system and can be used for district determination in establishing DMA systems for operational planning and effective NRW forecasting.

3.3.2. Indirect Factors. In this section, we analyzed the indirect factors related to social and economic factors. Because NRW is estimated based on measured data, it is difficult to expect and introduce social and economic parameters. The determination of NRW and physical and operational parameters is influenced by socioeconomic parameters; thus, regional characteristics and socioeconomic factors should be considered when evaluating operational data. This can support the analytical result of NRW.

Indirect factors are classified as socioeconomic factors and others. Socioeconomic factors have a social element representing the population density of a district and can be used to consider the characteristics of urban and rural areas. These parameters differ depending on the grade of urban development. Densely populated areas tend to have shorter water pipe lengths and a lower NRW because of the higher probability of preventing water leaks.

Financial and economic factors indicate the financial strength of a city and the economic life of residents. Developed economies have higher budgets for social infrastructure than those of developing economies, and quality control is performed periodically. Developed economies also are highly likely to use high technology in the operation and management of water distribution systems. These financial and economic factors help us to reduce leaks by reducing their occurrence and optimizing a pipe network's operation.

Financial performance parameters can be connected as an extension of the secondary factor of economic and financial components. An efficient financial system leads to better financial performance that in turn leads to long-term investment and management of water infrastructure and holds an advantage in designing projects such as increasing the revenue/water ratio. Cost and staffing are parameters related to staff works, recruitment, and management fees for waterworks operations. Optimal cost management and staff operations are expected to decrease the occurrence of leaks.

Billing and collection include a factor that determines whether billing is regularly collected. A higher water rate results in a greater advantage, and billing and collection helps in managing infrastructure. Funding is essential for the periodic rehabilitation of existing facilities and introduction of new equipment. In addition, appropriate collection of water fees can be used to invest in water infrastructure. Among indirect factors, user satisfaction shows the grade of optimization in efficient restoration and minimization of operational problems from accidental parameters that can occur in the water distribution networks such as pipeline breakage and leaks. A key task is realizing the indicators because of the potential for personal opinions to be reflected by users and operators. Waterworks system should be developed to quantify user opinions.

Table 6: Final selected parameters for NRW management [4, 8, 36–38].

Classification	Parameters	Application area
Physical	(i) Pipe material (ii) Mean pipe diameter (iii) Pipe length per number of demand junctions (iv) Amount of water supply per number of demand junction (v) Deteriorated pipe ratio	Administrative area, DMA
Operational	(vi) Number of leaks (vii) Leak recovery ratio (viii) Demand energy ratio	
Socioeconomic	(ix) Water price cost recovery rates (x) Investment ratio of maintenance cost to expenditures (xi) Investment ratio of facility improvement cost to expenditures (xii) Population of water supply per number of demand junctions (xiii) Fiscal self-reliance ratio	Administrative area

4. Final Parameter Selection for NRW Management

The final selected parameters via the classification system described in Section 3 are shown in Table 6. The selected parameters are determined based on parameters that can be quantified. Qualitative parameters are classified according to local characteristics. If parameter quantification is possible, qualitative parameters can be used via an additional data conversion process. Based on the parameters selected via the factorization scheme described in Section 3, parameters including subcategorization based on quantifiability were selected.

Among the all parameters described in Section 3.2, the selected physical parameters are mean pipe diameter, pipe material, amount of water supply per number of demand junctions, pipe length per number of demand junctions, and deteriorated pipe ratio. Operational parameters include the number of leaks and the ratio of energy demand and leak recovery.

Among the socioeconomic parameters, parameter classifications and qualitative parameters are selected. As socioeconomic parameters, the population of the water supply per the number of demand junctions, fiscal self-reliance ratio, water price cost recovery rates, and the investment ratio of maintenance costs for facility improvement to total expenditures were determined.

Data acquisition from DMAs and socioeconomic parameters is difficult while physical and operational parameters are applicable in DMAs and administrative districts. To apply socioeconomic parameters, the acquisition of statistical data is required and is completed by subdividing DMA data into administrative districts because it depends on measured data classified into administrative districts. Thus, analyses of the specific region where waterworks statistics data are available are necessary for the data collection on physical, operational, and socioeconomic parameters.

5. Conclusions

A parameter classification process for NRW management was suggested for water distribution systems. For this purpose, the major water leakage parameters and the factors related to NRW in a water distribution network were investigated. In particular, the process was classified according to the characteristics of the parameters, and quantitative and qualitative parameters were classified to help in NRW management using statistical analysis.

The generation of the parameter classification process was based on the physical, operational, and socioeconomic parameters that can use for NRW analysis. This classification system can be applied to NRW management using the quantified data of selected parameters. The study determined if the parameters related to a water distribution system were more appropriate for physical, operational, or socioeconomic factors and classified them into one of these three categories.

To increase the accuracy of NRW management, socioeconomic parameters such as fiscal self-reliance ratio, population of water supply per demand junction, water price cost recovery rates, investment ratio of facility improvement cost to expenditures, and investment ratio of maintenance cost to expenditures are required. It is anticipated that the NRW accuracy will be improved if additional socioeconomic factors can be expressed by physical and operational parameters.

If the accuracy of NRW prediction is low using the direct factors, it is recommended that NRW prediction be applied using socioeconomic factors. Socioeconomic factors are considered to be helpful in explaining complex NRW phenomena that have limited data acquisition such as administrative districts and DMAs but cannot be explained by physical factors.

Because socioeconomic parameter data in water distribution networks are acquired from administrative districts, a disadvantage is that data acquisition for a DMA is difficult. Thus, one solution for NRW management is a data utilization system for data collection and research that can quantify the classification system of the unquantified data. It is expected that more accurate NRW management will be possible if a data utilization system is activated. In addition, cooperation among administrative districts for data provision should be implemented.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

The Last Mile: Safety Management Implementation in Construction Sites

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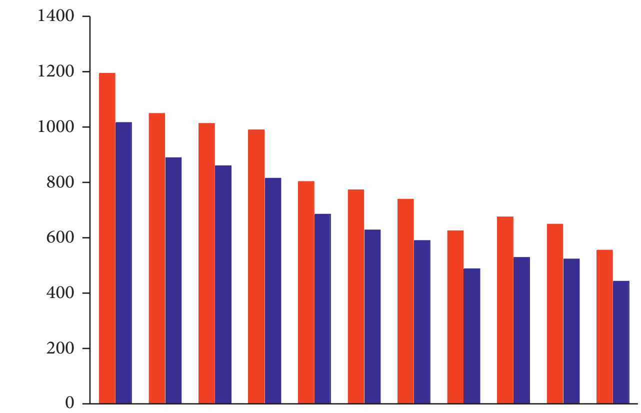
To deepen the understanding of the construction safety accidents rules as well as identify and cure the crux of construction safety management failures in China, we analyzed the status quo of safety management and identified the "last mile" problem, that is, the failure of implementation of the extensive legal and regulatory systems on the construction site. The safety factors were then extracted based on a questionnaire consisting of 34 items. Through factor analysis and ranking correlation, five human factors were found to be the greatest challenge and leverage point of safety management at construction sites. Accordingly, a novel safety management framework was proposed and tested as part of the Wuhan-Shenzhen highway project. Expert auditing confirmed that the proposed framework could substantially improve the construction safety performance and thus bridge the "last mile" of safety management implementation.

1. Introduction

As has been shown in different countries around the world, construction is among the most unsafe industries because of its unique nature [1, 2]. Nowadays, projects are carried out at an increasing rate and complexity, and accidents are leading to greater repercussions [3, 4]. Regrettably, the booming construction industry has always been accompanied by many accidents and deaths, which is especially true in developing countries like China. The mortality rate in the Chinese construction industry has long sustained unacceptably high numbers, contributing to tremendous monetary losses as well [5].

Many countries have implemented laws and regulations to strengthen safety management in their construction industry, most importantly to prevent accidents and reduce deaths [6, 7]. In China, the Production Safety Law [8] was promulgated in 2002, specifying how safety should be guaranteed, how employees should meet their obligations and exercise their rights, how safety should be supervised and administered, and how accidents should be handled. In 2004, the Administrative Regulations on the Work Safety of Construction Projects [9] took effect, which further defined and divided the liabilities among various entities in charge of construction, survey, design, and supervision. The national standard GB/T 28001-2011 on the "occupational health and safety management system" [10] was issued in 2012. Over the past decades, China has gradually built a systematic safety management standard and introduced appropriate laws. In China, the accident level is divided into minimal, moderate, high, and disastrous listing based on economic losses and number of deaths and serious injuries reported. The project manager is required to contact and report to the local safety supervision department within 1 hour of the accident. Based on the severity of the accident, the local or higher government will then setup a professional team to investigate the cause of the accident. Concealment and omission of the accident are becoming more and more difficult and costly because of the sound and rigorous legal and media supervision. The bureau of statistics has reported that the annual construction accidents from all projects throughout China have declined from 1193 in 2005 to 554 in 2015, which gratifyingly shows a decreasing trend (Figure 1).

Though the number of construction accidents is decreasing, statistics also show that the average death per accident has stayed largely consistent at 1.24 over the past



Years	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Deaths	1193	1041	1012	989	802	772	738	624	670	648	554
Accidents	1015	882	859	814	684	627	589	487	524	522	442

Figure 1: The number of accidents and deaths in the construction industry in China (2005–2015).

decades (Figure 1). This unveils some persisting issues, despite the encouraging decline in the number of accidents. We see this as a typical "last mile" problem and ascribe it to the gap between the actual safety practice on site and the existing laws, regulations, standards, and systems of safety management. Specifically, safety management and supervision systems have been well devised at all levels, from the government to construction companies and further down to project groups. However, without a mechanism for self-adjustment in each project, the constantly changing situations on site, as well as human error, can prevent the externally designed safety management systems from working. Accidents result from operations violating safety rules that are carried out to deal with an unexpected and temporary concern. Here, we find the "last mile" problem—the failure to implement extensive legal and regulatory systems on construction sites.

To overcome this problem and improve the construction safety management performance, we intend to find the leverage points of safety management implementation, defined as "places within a complex system (a corporation, an economy, a living body, a city, and an ecosystem) where a small shift in one thing can produce big changes in everything" [11]. Further, the corresponding prevention and control measures are designed to work on these leverage points, thus bridging the last mile. The remainder of the paper is organized as follows: in Section 2, we provide an extensive literature review on construction safety measures in several countries and we introduce a theoretical framework with possible influencing factors. Section 3 presents our methodology, including the design and response of our questionnaire. Section 4 analyzes the safety management at construction sites, identifies the main challenges, and discusses the leverage points. Section 5 presents a case study that adopted the recommendations derived from the leverage points and the subsequent improvement in project safety. Conclusions are drawn in Section 6.

2. Literature Review

Factors that influence safety management at construction sites have been previously categorized into macro-, meso-, and microlevels, corresponding to sector/country factors, organizational factors, and human factors, respectively [12]. A similar classification [13] was applied to aggregate variables in the system of Occupational Safety and Health (OSH). In this work, we adopt an eventual division of factors into macro-, meso-, and microlevels.

2.1. Macrolevel Factors. In any developed country, safety is a crucial issue in the construction industry. Safety legislation and policies have been developed around the globe over the past decades (Table 1 for selected examples), having a great impact on the construction site safety. These legislations regulate and control health and safety on the macrolevel [14].

Furthermore, national safety management systems have been devised and adopted in many countries on the basis of appropriate standard practices. Depending on the specific requirements, these systems differ among countries with regard to the factors considered. For example, Wokutch and VanSandt extracted 8 key factors as the main frameworks of OHS management in the United States [15]. Fang et al. discussed empirical research done on workplace safety management performance on construction sites in China. Eleven factors that correlate closely with onsite safety management performance were identified to establish national safety management systems [16]. Teo and Ling discussed the safety management system (SMS) which had been applied to the construction industry for about 10 years in Singapore, though the improvement in safety standard is not significant. In response to the need to improve the effectiveness of the SMS and SMS audit, they divided 14 main safety management elements in SMS [17]. Ismail et al. compared the safety management system (SMS) adopted by various countries around the world and then identified the factors influencing the implementation of a safety management system for construction sites in Malaysia [7]. By reviewing and summarizing the research results of different scholars on the composition of their own SMS system, Table 2 provides a summary of the macrolevel safety factors included in the safety management systems [14–20].

2.2. Mesolevel Factors. Construction companies have diverse safety cultures, safety climates, working conditions, and habits [21]. These company factors reside on the mesolevel. The Post-Accident Review Meeting on the Chernobyl Accident by the International Atomic Energy Agency (IAEA, 1986) for the first time established the term "safety culture," including it in INSAG's Summary Report. Safety culture involves the values, beliefs, and attitudes shared within a group [22]. Choudhry et al. [23] reviewed safety culture, examined its definition, empirical evidence, and theoretical development, and proposed how to systematically analyze safety culture. The analysis recognized elements in the organizational, situational, technical, and human aspects, as well as interactions between these elements. Chinda [24] delved deeper into the

Table 1: Laws and regulations of various countries on safe production.

Country	Effective since	Title
UK	January 1974	The Health and Safety at Work
	April 2015	Construction (Design and Management) Regulations 2015
USA	September 1970	Occupational Safety and Health Act
	February 1926	Part 1926 of the OSHA standards
Singapore	January 1948	The Factories Act (Chapter 104)
	September 1999	Singapore Code of Practice on Construction Safety Management System
	1994	Building Operations and Works of Engineering Construction
China	November 2002	Production Safety Law of the People's Republic of China
	February 2004	Administrative Regulations on the Work Safety of Construction Project
Hong Kong	June 1997	Factories and Industrial Undertaking Ordinances
	June 1997	Occupational Safety and Health Ordinances

interactions between the key elements of construction safety culture, enablers, and goals, and within the enablers themselves. Molenaar et al. [25] characterized five latent variables to describe safety culture in a company. Gilkey et al. [26] evaluated the risk perception, safety culture, and safety climate in a residential construction project at Denver, Colorado.

The term "safety climate" was coined by Zohar [27] in studying safety attitudes in Israeli manufacturing. In contrast to safety culture, it refers to how the employees collectively perceive the organization's practices, procedures, and policies, as well as how they value safety in the organization [28–31]. It is often regarded as a key indicator of improving workplace safety [32]. Statistically significant correlations were found between safety climate and personal characteristics, such as education level, marital status, gender, direct employer, and drinking habits [33]. Lin et al. [34] found three key factors for successful safety climates: safety awareness, safety competence, and safety communication. Choudhry et al. [35] identified ten dimensions of a successful safety climate, such as competence, risk-taking behavior, safety resources, and improper safety procedure. Stoilkovska et al. [36] incorporated three facets into their measure of safety climates: (1) management commitment, (2) workers' commitment, and (3) safety inspections and perceived accident rate. The model of Liao et al. [37] comprised seven dimensions, such as supportive environment, supervisory environment, work pressure, and personal appreciation of risk.

The safety climate and safety culture are related independent concepts despite of their similarity in definition to some extent [38]. Safety climate can be considered a "snapshot" of safety culture [39]. In other words, the safety culture acts behind safety climate [40], and the latter is the manifestation of the former [41]. Nevertheless, both of them are closely related to the safety management of the construction enterprises and should be given high priority.

2.3. Microlevel Factors. The human factor in construction accidents has been explored extensively. It is commonly acknowledged that unsafe behavior underlies workplace accidents [42] and worker behavior must be proactively managed. Choudhry and Fang [6] conducted a series of interviews within the Hong Kong construction industry to determine reasons for unsafe behaviors. Their findings included disinterest in safety, failure to obey procedures, and lack of safety knowledge. Specifically, disinterest in safety was characterized by failure to identify unsafe conditions, lack of skill or training, unsafe work conditions, and not wearing personal protective equipment (PPE). Using the Bayesian network theory, Zhou et al. [43] quantified the links among five safety climate factors and four personal experience factors. They then used the survey data from Gammon Construction Limited and assessed, using their methodology, whether candidate strategies can improve safety behavior. Saurin and de Macedo Guimaraes [44] examined the workers' perceptions on scaffolding safety and determined that poor and stressful working conditions resulted from the combination of uncomfortable work posture, failures in safety planning and control, inappropriate inspections, and inadequate PPE use. Zheng et al. [45] suggested that, in central China, nonfatal construction injuries are high throughout the year, and the major risk factors for which were found to include the lack of injury prevention and safety education, serious cigarette smoking and/or alcohol consumption, and depressive symptoms. Jitwasinkul and Hadikusumo [46] identified seven important factors that affect safe behaviors in the construction industry of Thailand. Leung et al. [47] and Hung et al. [48] argued that construction workers' ill-formed safety attitudes can give rise to safety issues and risky behaviors.

Chi et al. [49] emphasized supervision, PPE and safety devices, safety training, and proper site inspections. Mattila and Hyttinen [50] and Teo et al. [51] contended that the project manager should vigilantly monitor personnel behavior and rectify problems. They noted a few important process variables and also noted several personnel variables.

2.4. The Last Mile. On each level, factors have been analyzed by many researchers and solutions have been proposed. The safety production-related laws and regulations of construction industries in China and the system framework for construction enterprise safety management have gradually improved over the past few decades. These laws and regulations are to some extent mandatory. Nevertheless, there are always a few workers intentionally or unintentionally violating the laws and regulations because of their subjective initiatives responding to volatile environment. In other words, the proposals on the macro- and mesolevels cannot be effectively implemented on the construction site because of human factors. Therefore, how to translate these good proposals into emotional recognition and conscious action of every worker on the construction site is the key to

Table 2: Safety factors included in safety management systems adopted by some countries.

Safety factor	Australia	China	Finland	Jordan	Malaysia	Netherland	Singapore	Spain	Thailand	USA
Safety meeting		✓		✓						✓
Safety inspection	✓	✓		✓					✓	✓
Safety regulation enforcement		✓			✓	✓			✓	✓
Safety training	✓	✓	✓	✓	✓	✓		✓	✓	✓
Safety communication		✓			✓			✓	✓	✓
Safety cooperation		✓								✓
Management worker relationship		✓					✓			✓
Safety resources		✓							✓	✓
Personal competency			✓						✓	
Personal motivation				✓	✓				✓	
Equipment management	✓			✓					✓	
Program evaluation									✓	
Management commitment					✓		✓		✓	
Authority and responsibility			✓		✓	✓			✓	
Prevention planning								✓		
Emergency planning	✓							✓		
Safety controlling	✓				✓			✓		
Benchmarking								✓		
Incentive and punishment and recognition	✓						✓	✓		
Safety policy and statutory requirement				✓			✓	✓		
Management difficulty and subcontractors					✓		✓			
Safety attitude				✓			✓			
Safety analysis	✓					✓				
Safety organization					✓	✓				
Thematic approach						✓				
Clear goals			✓		✓				✓	
Availability					✓					
Construction cost optimization					✓					
Labor turnover rate				✓						
Work involvement			✓							
Management support	✓		✓							
Safety review	✓									

bridging the "last mile." In this work, instead of focusing on a single entity, we try to collect the views and opinions of every entity on construction sites and propose a new framework to tackle the "last mile" problem through an integrated analysis.

3. Methodology and Results

The research methodology is shown in Figure 2. The first step was to review the safety factors on each individual level and identify the "last mile" problem.

In step 2, relevant attributes were selected and collated based on the literature review, exploratory interviews (step 3), and the pilot study (step 4). A questionnaire was then designed to survey practitioners' perceptions of the importance of the collated attributes (step 5).

Data collected from the questionnaire was analyzed (step 6) to give five factors that are significantly related to the construction safety (step 7) and the weights of these factors (step 8). It was found that the items related to workers are the key leverage points (step 9), and a new framework for safety management was proposed accordingly (step 10).

A rating method was then developed (step 11) and verified by ten industry experts. Thereafter, the new framework for safety management was tested through two site audits. The feedback shows that the safety management on construction sites improved considerably. The results confirmed that the new framework could solve the "last mile" problem (step 12).

3.1. Questionnaire Design. Data on the views of various entities in construction projects were collected through a questionnaire to enable an objective and cost-effective investigation. First, a comprehensive list of safety factors was screened in a pilot study to ensure that all items in the questionnaire were valid, reliable, and significant. Then, item analysis was administered to see if an item itself could separate a participant from the rest. The results indicated that all items gave $p < 0.05$ and were thus significant. Zero was excluded from the 95% confidence interval of the difference.

Based on exploratory interviews and the above pilot study, we composed a questionnaire and solicited responses from several ongoing construction projects throughout China. The questionnaire contained two sections. The first section collected the general information of the respondents,

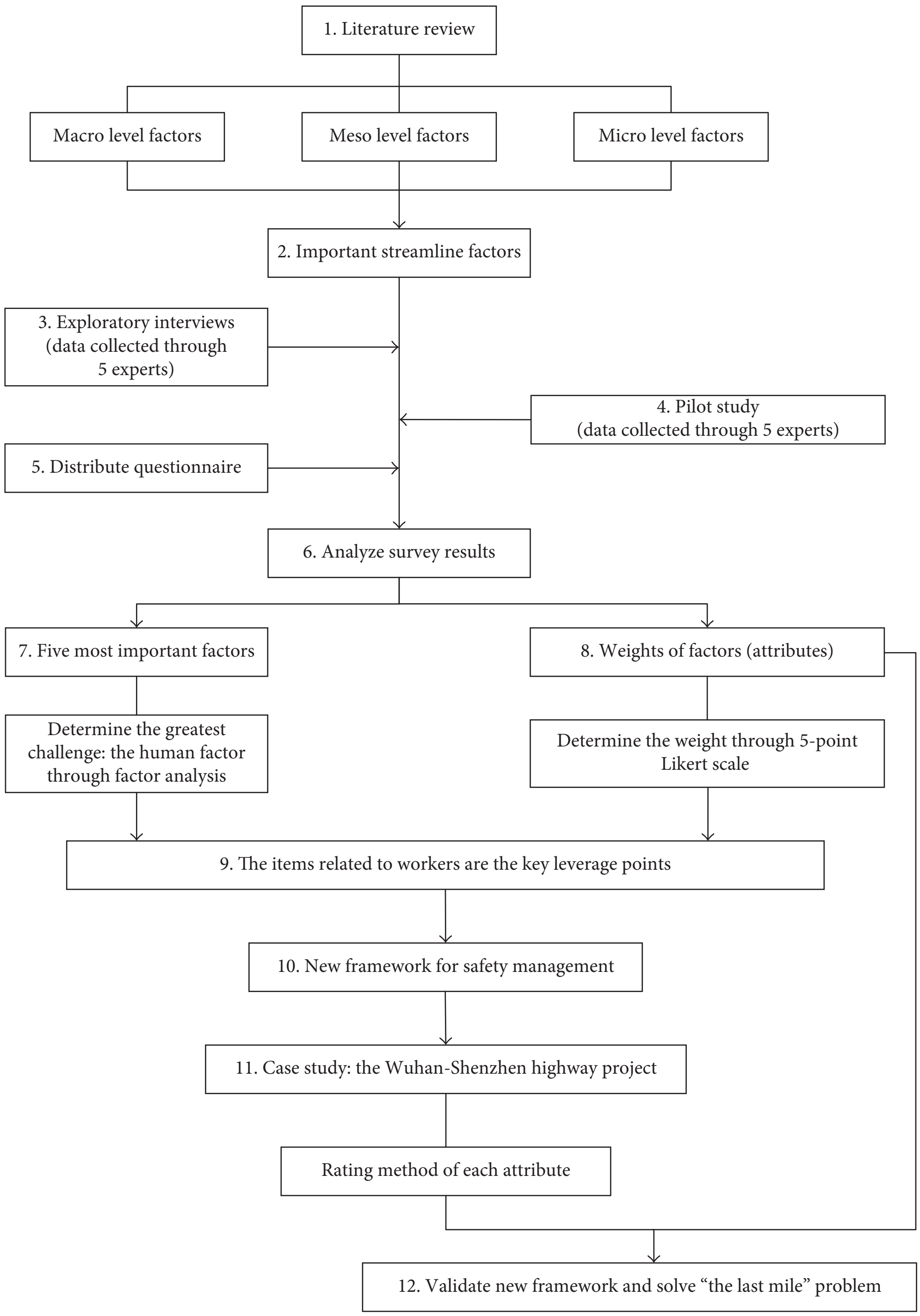


Figure 2: Research methodology.

and the second section consisted of 34 factors (listed in Table 3) that could potentially affect the safety management at construction sites. All items adopted a Likert-type scale for the answers, ranging from a value of 1 (not important) to 5 (extremely important).

3.2. Questionnaire Respondents. Responses were solicited from various entities at eight construction sites in three typically large projects under construction in central and eastern China, including proprietors, consultants, designers, contractors, and supervisors. Five of the eight construction sites are located in Wuhan section of the Wuhan-Shenzhen highway project, two of them are located in the Guandu Yellow River Bridge project, and the last one is located in the Wufeng Mountain Yangtze River Bridge project. The questionnaire survey was carried out in a voluntary and anonymous manner with the strong support and coordination of

Table 3: Questionnaire items.

Item	Key items
1	Safety attitude of workers
2	Safety behavior of workers
3	Safety training received by workers
4	The health and safety file
5	Safety meeting
6	Experience and skills of workers
7	Education level of workers
8	Personal protective equipment
9	Safety management commitment
10	Safety experience and skills of contractors and supervisors
11	Safety attitude of contractors and supervisors
12	Safety education and knowledge of contractors and supervisors
13	Proper installation and dismantling of plant and equipment
14	Maintenance regime for all equipment and plants
15	The reasonable choice of work equipment
16	Proper handling of all equipment and plants
17	Safety regulation and plan enforcement
18	Safety incentive and punishment
19	Safety risk identification and analysis
20	First aid and emergency preparedness
21	Safety inspection and guidance
22	Complexity of geology and hydrology
23	Frequency of adverse weather
24	Schedule and cost pressures
25	Allocation of safety responsibility
26	Effective communication and cooperation
27	Organizational capability of contractors
28	Evaluation, selection, and control of subcontractors
29	The complexity type and technique of construction
30	Quantity of workers on the construction site
31	Mobility of workers on the construction site
32	Complexity of surrounding environment
33	Welfare facilities
34	The numbers of modifying existing designs

the project owners. In total, 513 questionnaires were distributed and 447 valid questionnaires were retrieved, thus giving an effective recovery rate of 87.13%. The 12.87% invalid questionnaires were either incompletely answered or declined by the respondent to participate. Figure 3 shows the breakdown of the respondents of the 447 valid questionnaires in terms of age, years of work experience in construction, education level, and job duties.

The construction industry has advanced rapidly in China. As a result, the role of the project manager has been increasingly assumed by fresh graduates, where construction workers mostly come from rural areas and where education is poor. Inadequate experience is common among the personnel at project sites. Statistics in Figure 3 show that 39% of the respondents were 20–30 years old, 39.6% had 1–5 years of working experience in the construction industry, and 71% finished their education at, or below, the high school level. A further breakdown on the hierarchy of job duties shows that among the 447 respondents, senior managers accounted for 4.5%, middle managers for 24.3%, front-line managers for 38.2%, and workers for 33.0%.

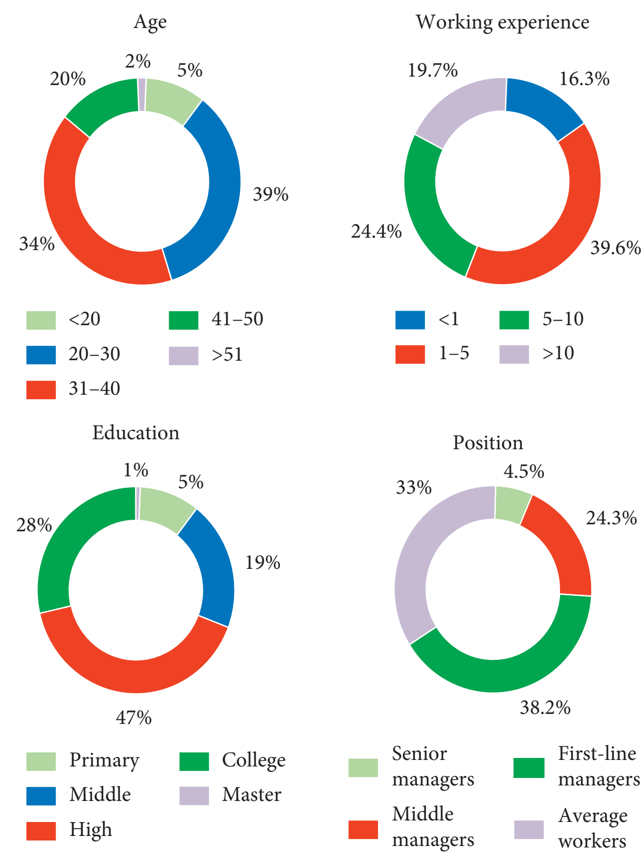


Figure 3: Segmentation in various dimensions of the 477 valid respondents.

3.3. Statistical Analysis. Collected data were analyzed with the Statistical Package for Social Science (SPSS 18.0) using the following techniques: (1) factor analysis, (2) estimation of mean value, (3) rank cases, (4) one-way analysis of variance (ANOVA), and (5) Spearman rank correlation.

Factor analysis relies on a set of common underlying dimensions, known as factors, to unveil the correlations among a large number of variables [16, 52–54]. The current analysis identified the major challenges in implementing the macro- and mesolevel management and supervision system during the day-to-day practices. Different participants assign different weights to the safety factors, and inspecting the discrepancy in their ranking can help to determine the leverage points in dealing with the challenges in safety management at construction sites, thus closing the "last mile." The current results have a high level of significance at $p < 0.01$, compared with the more commonly seen significance level of 0.05.

3.4. Five Significant Related Factors. Data were first checked with the KMO and Bartlett's tests in SPSS. Table 4 shows that the KMO test gives a result of 0.795, which has passed the cutoff of 0.5, and confirms that the items in the questionnaire have enough factors in common to allow for factor analysis. The approximate chi-square distribution is 1600.223 and arrives at the significance level $p \leq 0.001$ when the degree of

Table 4: KMO and Bartlett tests.

Kaiser–Meyer–Olkin metric for sampling sufficient degree		0.795
Bartlett test of sphericity	Approximate chi square	1600.223
	d.f.	561
	p	0.000

freedom is 561. The overall correlation matrix is thus not an identity matrix, and the factor analysis is valid.

The load factor refers to the correlation between variables in a factor. A factor can be synthesized by a number of variables in that after varimax rotation, principal component analysis gives a relatively high load factor between the derived variables. Variables are consolidated into common factors when possible, which then clarifies what these factors represent. Table 5 shows the resulting key safety factor dimensions, based on outlining the five challenges that are significantly related to construction safety as follows.

3.4.1. Challenge 1: Human Factor. This principal factor accounts for 32.986% of the total variance and exists in the following items:

(1) Safety attitude of workers
(2) Safety behavior of workers
(3) Safety training received by workers
(6) Experience and skills of workers
(7) Education level of workers
(10) Safety experience and skills of contractors and supervisors
(11) Safety attitude of contractors and supervisors
(12) Safety education and knowledge of contractors and supervisors
(26) Effective communication and cooperation
(30) Quantity of workers on construction sites
(31) Mobility of workers on construction sites

Among the abovementioned items, 1, 2, 3, 6, 7, 26, 30, and 31 can be attributed to the workers and items 10, 11, and 12 to the managers at the project sites. Thus, Challenge 1 can be defined as the human factor in safety management.

Based on the factor analysis theory [55], the above findings imply that human involvement in management routine has the greatest impact on safety at construction sites in China and is thus a key target for improvement.

3.4.2. Challenge 2: Equipment Factor. Factor 2 accounts for 14.324 of the total variance and is distilled from the following items:

(8) Personal protective equipment
(13) Proper installation and dismantling of plant and equipment
(14) Maintenance regime for all equipment and plants
(15) The reasonable choice of work equipment

Among the abovementioned items, 13–15 are concerned with mechanical equipment at the site, and item 8 is concerned with the personal protection of workers, such as gloves, helmets, and goggles, Thus, Challenge 2 can be defined as the equipment factor in safety management.

According to the statistics of the accident survey published by the National Bureau of Statistics, mechanical injuries are one of the five major types of accidents (Table 6), can incur substantial loss to both the construction company and the workers, and in extreme cases may even put workers in life-threatening situations. Therefore, mechanical equipment must be properly selected and used in accordance with standard operation procedures. To ensure safety, tower cranes and other machinery must be regularly and rigorously inspected, and workers must also receive and use necessary PPE.

3.4.3. Challenge 3: Environment Factor. Factor 3 accounts for 11.208% of the total variance and mainly covers the following items:

(22) Complexity of geology and hydrology
(23) Frequency of adverse weather
(24) Schedule and cost pressures
(32) Complexity of surrounding environment

These items reflect the influence of environment factors on safety management. Construction projects often have to deal with the adverse natural environment, and as the projects proceed, the project participants may create an artificial environment in which further challenges arise.

3.4.4. Challenge 4: Management Factor. Factor 4 entails the following items:

(4) The health and safety file
(5) Safety meeting
(9) Safety management commitment
(17) Safety regulation and plan enforcement
(18) Safety incentive and punishment
(21) Safety inspection and guidance
(25) Allocation of safety responsibility

All of the abovementioned come down to the management factors. A successful project requires good planning, organization, and coordination, and the influence of management on the workers and thus on project safety cannot be overlooked.

3.4.5. Challenge 5: Technical Factor. Factor 5 accounts for 7.684% of the total variance and involves the following items:

(19) Safety risk identification and analysis
(20) First aid and emergency preparedness
(29) The complexity type and technique of construction

Table 5: Rotated component matrix.

Item	Component 1	2	3	4	5	6	7	Variance (%)	Extracted common factors
2	**0.81**	0.095	0.098	−0.012	0.071	0.099	0.254	32.986	Human factor
3	**0.805**	0.044	−0.055	0.348	0.109	−0.054	0.08		
31	**0.746**	0.045	0.208	0.186	0.058	−0.266	0.211		
11	**0.724**	0.34	−0.012	0.176	0.122	0.258	−0.220		
1	**0.692**	0.138	−0.018	0.04	−0.105	−0.158	0.452		
26	**0.676**	0.514	−0.104	0.082	0.225	0.029	−0.028		
6	**0.654**	0.128	0.18	0.14	0.247	−0.056	0.21		
30	**0.619**	0.12	0.056	0.127	0.398	0.222	−0.034		
12	**0.613**	0.38	0.01	0.522	0.056	−0.022	−0.058		
7	**0.5**	0.364	0.336	0.224	0.251	−0.049	−0.200		
10	**0.449**	0.339	−0.222	0.351	0.309	0.164	0.1		
8	0.177	**0.706**	−0.014	0.182	0.203	0.102	0.236	14.324	Equipment factor
13	0.201	**0.696**	0.016	0.079	0.059	0.179	0.309		
15	0.148	**0.634**	0.165	0.335	0.001	−0.069	0.271		
14	0.207	**0.628**	0.336	0.191	0.115	−0.043	0.009		
32	−0.133	0.116	**0.752**	0.116	0.221	−0.033	0.047	11.208	Environment factor
23	0.18	0.244	**0.721**	0.072	−0.233	0.108	0.216		
22	0.068	−0.155	**0.681**	0.287	0.092	0.141	0.022		
24	0.236	0.009	**0.544**	0.089	0.283	−0.538	−0.043		
25	0.048	0.17	**0.437**	0.28	0.342	−0.371	0.328		
21	0.09	0.146	0.288	**0.664**	0.104	0.176	0.115	9.624	Management factor
18	0.259	0.154	0.184	**0.648**	0.203	−0.040	0.036		
17	0.27	0.259	0.154	**0.569**	−0.032	0.182	0.087		
9	0.485	0.081	0.041	**0.513**	−0.050	0.333	0.159		
5	0.059	0.305	0.009	**0.498**	0.423	−0.357	0.025		
4	0.333	0.238	−0.038	0.078	**0.688**	−0.030	0.083	7.684	Technical factor
20	0.224	−0.057	0.167	0.281	**0.652**	0.373	−0.043		
29	−0.029	0.037	0.357	−0.011	**0.609**	−0.103	0.285		
19	0.396	0.322	0.155	0.046	**0.538**	−0.215	0.197		
16	−0.058	0.078	0.088	0.291	0.004	**0.735**	0.137	4.493	/
33	0.168	0.29	0.524	−0.082	0.178	**0.557**	−0.083		
27	0.082	0.207	0.113	0.156	0.18	0.133	**0.735**	2.864	/
34	0.43	0.259	0.093	−0.049	0.129	−0.103	**0.633**		
28	0.227	0.38	0.04	0.266	0.075	0.405	**0.562**		

Table 6: Breakdown of construction accidents in China (2008–2015).

Accident types	2009	2010	2011	2012	2013	2014	2015	Mean
Falling injuries (%)	51.90	47.37	53.31	52.77	46.15	54.57	53.17	51.32
Collapses (%)	13.74	14.83	14.60	13.76	19.23	11.75	13.36	14.47
Object strikes (%)	12.28	16.75	12.05	12.11	13.85	12.53	14.93	13.50
Crane machine accidents (%)	6.43	7.02	8.32	10.27	10.77	8.36	7.24	8.34
Electric shocks (%)	4.09	4.63	5.09	2.05	3.15	4.41	4.07	3.93
Others (%)	11.56	9.40	6.63	9.04	6.85	8.38	7.23	8.44

The abovementioned items may be considered as technical factors. The technical staffs are in charge of selecting the most suitable technique and training the workers. Poor choice of the technique may undermine safety. In fact, two additional factors have also been extracted, the first from items 16 (proper handling of all equipment and plants) and 33 (welfare facilities), the second from items 27 (organizational capability of contractors), 28 (evaluation, selection, and control of subcontractors), and 34 (the numbers of modifying existing designs). Although they are statistically significant, they are not interpreted further because we do not see an explanation that corresponds to reality. For example, it is difficult to argue what kind of unique factor is in common within the items "proper handling of all equipment and plants" and "welfare facilities."

The Cronbach's alpha coefficient refers to the degree of consistency among different items within a certain dimension. It is a commonly used reliability index. In order to ensure the appropriateness of grouping the five extracted common factors, the consistency of each common factor was tested using the Cronbach's alpha coefficient. The results are

Table 7: Results of Cronbach's alpha reliability test.

Extracted common factors	Cronbach's alpha coefficient
Human factor	0.774
Equipment factor	0.872
Environment factor	0.716
Management factor	0.762
Technical factor	0.814

shown in Table 7. The alpha coefficient of each common factor is greater than the minimum expected value of 0.70 within the interval of (0.716, 0.872), indicating that each dimension has good internal consistency [56, 57].

3.5. Weight of Importance for Factors and Ranking Consistency between Participants. Estimation of the mean value shows that the top five most important items are the following:

(2) Safety behavior of workers
(1) Safety attitude of workers
(5) Safety meeting
(3) Safety training received by workers
(32) Complexity of surrounding environment

One-way ANOVA is detailed in Table 8 to show if there are significant differences among the influence of proprietor, consultant, designer, contractor, and supervisor on safety factors.

In Table 9, the Spearman rank correlation shows remarkable inconsistency between the proprietor and the designer. The contractor and the designer have a consistency at the level of 0.01. The supervisor has a consistency level of 0.01 with all other entities, mainly because the supervisor coordinates them and resolves their conflicts.

3.6. Key Leverage Points. In Figure 4, we propose a model on construction safety according to our data. According to the contribution of 5 extracted common factors to the total variance in factor analysis (Table 5), the human factor presents the greatest challenge and is shown as the blue pillar in the middle. Note that the managers and the workers contribute differently to the human factor. This section looks for possible leverage points to fortify this blue pillar. We seek to identify elements within the human factor that could be reconditioned to foster safety management at construction sites and consequently bridge the "last mile."

The results of ANOVA show that there are some disagreements among the different entities on the main influencing factors of construction safety. At a significance threshold of 0.001 in ANOVA, the following five items were rated very differently by different respondents:

(7) Education level of workers
(17) Safety regulation and plan enforcement
(18) Safety incentive and punishment
(21) Safety inspection and guidance
(29) The complexity type and technique of construction

Designers gave low rating to item 7, mainly because design and engineering are relatively independent stages in construction projects, and designers often assume by default their plan can be carried out by the workers without thinking about the background and capability of said workers. Item 18 received the highest rating from the proprietors. Most contractors claimed that, for an accident having no more than three deaths, the punishment is acceptable. Some contractors are even more willing to pay the fine than invest in safety, whereas the proprietors think that raising the fine can incentivize the contractors to improve safety. Item 21 received a low rating by all respondents except proprietors. Our interviews showed that although proprietors fully authorize supervisors regarding safety issues on the site, in reality, the supervisors have a low status. They are not readily welcomed by others and do not receive good cooperation, impairing their control over the projects. Both consultants and proprietors gave high ratings to item 17 and item 29 because they lack technical experience and are more concerned with the impact of engineering technique on safety.

The Spearman rank correlation analysis shows that proprietors and designers seriously disagree as to what are the top safety factors. They are both concerned with the workers' safety training and consider item 3 as the second most important safety factor, while the other four in their lists of top five were completely different. Designers are concerned with the following items:

(32) Complexity of surrounding environment
(22) Complexity of geology and hydrology
(23) Frequency of adverse weather
(2) Safety behavior of workers

For the proprietors, among these items only item 2 was ranked 9th while the others were considered much less important. Items 22, 23, and 32 focus on the complexity of the environment, which may heavily impact the realization of the design. The designers must test their plan under a variety of extremely adverse conditions to ensure safety and are thus highly concerned with the environmental factor.

Despite the differences of opinion on the abovementioned items, all respondents considered the items related to workers to be very important for safety. The safety behavior of workers (item 2), safety attitude of workers (item 1), safety training received by workers (item 3), experience and skills of workers (item 6), and education level of workers (item 7) were ranked the first, second, fourth, sixth, and tenth in the combined ranking from all 447 valid questionnaires. Therefore, considering the results of the Factor analysis and the Mean and ANOVA analysis synthetically, within the human factor, which itself is the number one challenge, the items related to workers are the key leverage points in safety management, including the safety behavior of workers (item 2), safety attitude of workers (item 1), safety training received by workers (item 3), experience and skills of workers (item 6), and education level of workers (item 7). The performance of the five

Table 8: Mean and ANOVA analysis.

Item	Overall		Proprietor		Consultant		Designer		Contractor		Supervisor	
	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
2	4.2054*	1	3.86	9	3.84	9.5	4.04	4.5	4.21	1	4.23	1
1	4.1027*	2.5	3.35	19	4.18	2	2.69	33	4.07	2	4.05	3.5
5	4.1027*	2.5	3.76	10	4.20	1	3.86	8	3.93	7.5	4.12	2
3	4.0622**	4	4.17	2	3.96	7	4.22	2	4.05	3	4.01	6.5
32	4.0351**	5	3.34	20.5	3.18	25	4.24	1	3.79	9.5	4.03	5
6	3.8876	6.5	3.28	24.5	3.56	19.5	3.57	17.5	3.96	4.5	4.05	3.5
8	3.7976	6.5	2.96	28	3.69	14.5	3.75	11.5	3.93	7.5	3.88	9.5
18	3.7865**	8.5	4.20	1	4.16	3.5	3.59	16	3.69	14	3.77	12.5
29	3.6865**	8.5	4.07	4.5	3.74	11	3.64	14.5	3.66	15.5	3.28	15.5
7	3.6595**	10	3.70	11	3.16	26	3.57	17.5	3.96	4.5	4.01	6.5
9	3.6459*	11.5	4.16	3	4.16	3.5	3.21	26.5	3.79	9.5	2.86	18.5
11	3.6459*	11.5	3.45	16.5	3.84	9.5	3.75	11.5	2.69	32	3.88	9.5
26	3.5819**	13	3.28	24.5	3.76	10	3.44	20	3.66	15.5	3.89	8
12	3.5749	14	3.69	12.5	3.71	12.5	3.27	22.5	3.77	11	3.59	14
19	3.5703	15	3.95	7.5	3.56	19.5	3.78	9.5	3.75	12.5	2.99	17
10	3.5568	16	3.95	7.5	3.56	19.5	3.66	13	3.75	12.5	2.86	18.5
17	3.5027**	17	3.96	6	3.23	23.5	2.99	30	3.48	19	3.79	11
25	3.4892	18	3.34	20.5	4.07	5.5	3.38	21	3.44	21	2.86	18.5
27	3.4849	19	3.43	18	3.09	27.5	3.48	19	3.65	17.5	2.78	23
31	3.3811**	20	2.91	29	3.09	27.5	3.64	14.5	3.28	23.5	3.77	12.5
24	3.3676	21	3.32	22	3.69	14.5	3.88	6.5	3.95	6	2.77	24.5
20	3.3270	22	2.90	30.5	3.69	14.5	3.88	6.5	3.45	20	2.69	26
21	3.2459**	23	4.07	4.5	2.97	29.5	3.22	25	3.32	22	2.86	18.5
13	3.2323	24	2.80	32.5	2.76	34	3.26	24	3.65	17.5	3.28	15.5
28	3.1514	25	2.53	34	4.07	5.5	3.21	26.5	3.19	25.5	2.77	24.5
34	3.0378	26	3.69	12.5	3.69	14.5	3.78	9.5	2.89	29	2.67	27.5
15	2.9943*	27	2.80	32.5	2.78	33	3.21	26.5	3.28	23.5	2.87	22
4	2.9938	28	3.57	14	3.23	23.5	3.27	22.5	2.86	30.5	2.44	29
16	2.9697	29	3.45	16.5	3.59	18	2.76	32	3.19	25.5	2.42	32
30	2.9662	30	3.30	23	2.80	32	3.21	26.5	2.86	30.5	2.43	30.5
22	2.9595**	31	2.90	30.5	3.71	12.5	4.13	3	3.29	25.5	2.67	27.5
14	2.9054	32	3.22	27	2.97	29.5	2.77	31	3.29	25.5	2.26	34
23	2.7973	33	3.53	15	3.56	19.5	4.04	4.5	2.68	33	2.43	30.5
33	2.527	34	3.23	26	3.89	8	2.44	34	2.47	34	2.28	33

*Significant at the 0.05 level (two-tailed); **significant at the 0.01 level (two-tailed).

Table 9: Spearman rank correlation coefficients.

	Proprietor	Consultant	Designer	Contractor	Supervisor
Proprietor	1.000	—	—	—	—
	—	—	—	—	—
Consultant	0.352*	1.000	—	—	—
	0.026	—	—	—	—
Designer	0.232	0.352*	1.000	—	—
	0.150	0.026	—	—	—
Contractor	0.395*	0.402*	0.479**	1.000	—
	0.012	0.010	0.002	—	—
Supervisor	0.450*	0.604**	0.682**	0.711**	1.000
	0.004	0.000	0.000	0.000	—

*Significant at the 0.05 level (two-tailed); **significant at the 0.01 level (two-tailed).

items is closely related to the performance of construction safety management and is the key to solving the "last mile" problem. Since construction workers usually work in groups and teams, we propose a novel management framework in the next chapter to motivate the workers to safely react to spontaneous problems, thus bridging the "last mile."

4. New Framework for Safety Management

The construction site is a complex system, in which workers are the only entity that can adjust on its own. To lever the five leverage points identified above and amend the "last mile" problem in safety management, we propose a new organizational framework that can transform the top-down safety

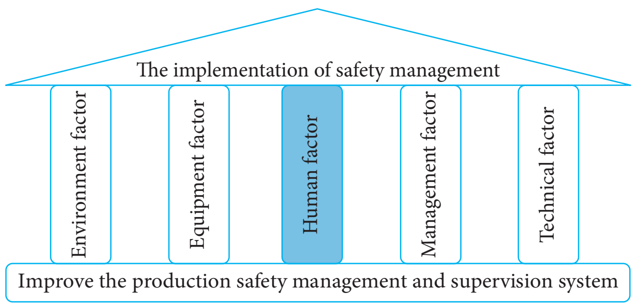


Figure 4: Safety factors and new framework for safety management.

management into bottom-up safety behavior. The core of the framework is to strengthen the guidance and supervision of the leaders above workers and the mutual guidance and supervision of the workers on construction sites, greatly improving the performance of the workers on the five leverage points.

4.1. Making Leaders Ubiquitous. At construction sites, safety issues can arise in any moment at any place, so external ever-present supervision and guidance is crucial for improving the safety behavior (item 1) and safety attitude (item 2) of workers. In other words, the leaders must be ubiquitous and always be prepared to solve problems quickly and efficiently. They must have the necessary technical skills, management ability, and a strong sense of responsibility.

As the organizational chart in Figure 5 shows, the few number of people in senior management positions make it impossible to serve the engineering and operation teams on a constant basis. The absence of leaders causes frequent accidents. To ensure safety management, leaders must be in their post at all times such that no worker would go to a duty without having the leader standing by on call.

4.2. Appointing Leaders. As mentioned above, a good leadership team is crucial for safety management on the construction site. Leaders should be appointed mainly based on technical skills, following the priority outlined below:

(1) The full-time safety management personnel in the project department is the leader of all working faces and public spaces.

(2) In the absence of (1), the registered or assigned administrative team leader or group leader for a particular working face or public space takes charge of all safety issues.

(3) In the absence of (2), the project manager should automatically become the leader when entering a particular working face or public space.

(4) When only workers are present, whoever entered the task area first should be the leader for that area.

(5) Among the workers who entered the task area at the same time, the most senior worker should be the leader.

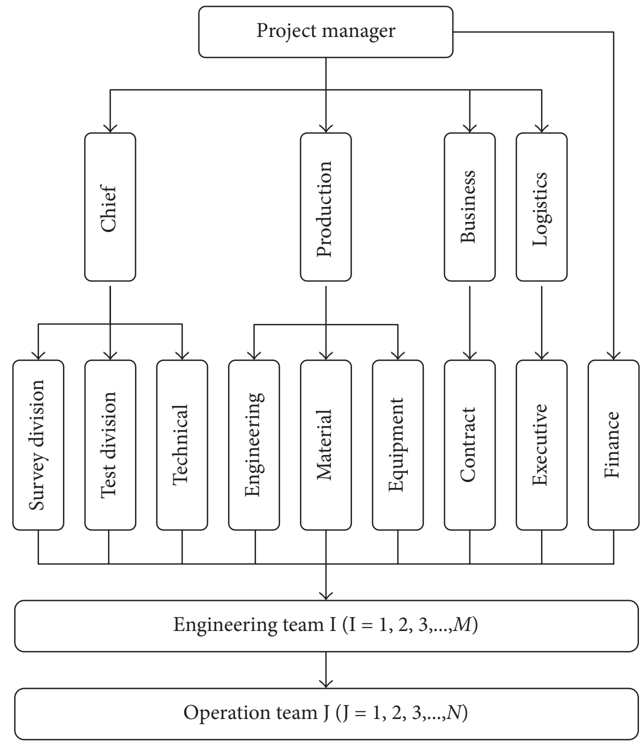


Figure 5: Typical organization structure for civil engineering projects in China.

In this way, the task area is always covered by a safety leader, helping eliminate accidents and minimize risks.

4.3. Pairing and Banding. As shown in Figure 3, worker's age, education, and work experience differ widely. Relatively speaking, workers with more experience and skills and higher education level have shown better performance in safety [55], which is consistent with the statistical analysis results in this paper. That is, safety training received by workers (item 3), experience and skills of workers (item 6), and education level of workers (item 7) are the key leverage points in safety management. Therefore, the mutual guidance and supervision of the different workers is also crucial for improving construction safety performance. Safety is not a one-man task, and all workers need to be covered by a teammate in situations where the person's own sight or ability may fall short. We thus propose that each day before work, workers should reaffirm who are their safety partners for the day and know for whom they must be keeping watch over. The pairing and banding scheme is described below in Table 10.

5. Case Study

To test how effective the proposed framework is in enhancing safety, we invited two safety experts, both of whom participated in the design of the questionnaire and in drafting the new framework for safety management, to conduct a case study and audit the safety management of a project before and after introducing the new framework.

Table 10: The Pairing and Banding scheme.

Pairing	Banding
(1) All members of a working group must have a safety partner. The assignment must be clearly understood and documented, either in writing or on a chart.	(1) Set up bands across pairs and workgroups with shared responsibility on safety during work. Two or more workers must coordinate during their task and ensure the safety of each other.
(2) Before starting work, the group leader should reaffirm or adjust the pairing assignment based on the attendance of the day and other personnel changes. In every task, the workers must make sure the pairing scheme takes effect and fulfill their responsibility.	(2) Partners should constantly alert each other during work: (i) Remind the partner of unsafe behaviors and situations to prevent accidents from happening. Maintain correspondence through calling and answering. (ii) Mutual caring: allocate tasks reasonably and help each other during work. (iii) Mutual supervision: make sure the partner strictly follows standards on wearing protective equipments and adheres to safety procedures and regulations.
(3) Partners should be paired in a complementary manner, for example, the junior with the senior, the old with the young, the male with the female, the strong with the less powerful, the hasty with the calm, and the bold with the diffident.	(3) Whenever necessary, remind workers other than the designated partner of unsafe behaviors and situations to prevent accidents from happening. Maintain correspondence through calling and answering.

5.1. Studied Object. The case study was carried out at the Wuhan section of the Wuhan-Shenzhen highway project (Figure 6). This highway is designed to have six lanes in two ways with a roadbed width of 34.5 m and a speed limit of 120 km/h. Grand bridges are designed to be robust against three-hundred years of flooding, and all other bridges robust against one-hundred years of flooding. The connecting lines follow the Class II road standard and have a speed limit of 60 km/h and a roadbed width of 12 m. The entire section is designed to withstand Level I vehicle loading. It spans about 33 km and is subcontracted into five project sites. The engineering tasks mainly involved works on the roadbed, bridge, and protective devices. The five project sites were similar in both natural environment and engineering works, and thus they were suitable for the case study.

Figure 6: The Wuhan-Shenzhen highway project.

5.2. Rating the Construction Site for Each Attribute. The ideal rating method should allow the safety auditors to evaluate the attributes in an objective and straightforward manner, while minimizing the disparity between their evaluations of the same site at the same time [17]. Based on two expert interviews, four possible rating options were designed:

(i) Binary: all attributes receive a mark of either zero or one.

(ii) Continuous: all attributes receive an arbitrary value between zero and one.

(iii) Binary with N/A: all attributes receive a mark of zero or one, or be marked as not applicable.

(iv) Continuous with N/A: all attributes receive an arbitrary value between zero and one, or be marked as not applicable.

(1) Binary

In this rating scheme, "0" indicates negative and "1" indicates "positive." This is objective and straightforward and thus is the most commonly used rating scheme.

(2) Continuous

This rating scheme is normally applied to an attribute that is assessed based on a set of samples. The score is obtained through dividing the number of samples that meet a certain criteria by the total number of samples evaluated.

(3) N/A

An attribute is marked N/A only when it is irrelevant in the context of the given construction project.

After the attributes were marked, scores were calculated as follows:

$$\text{Score } (S_1) = \text{weight } (w_1) \times \text{rate } (r_1), \tag{1}$$

where S_1 is the score for Attribute 1, w_1 is the relative normalized weight of Attribute 1, and r_1 is the auditor's assessment of Attribute 1 for a specific construction site. The attribute is the factor in the questionnaire.

The final audited safety management score was then summed as follows:

$$\text{CSI}_\text{i} = \sum_{j=1}^{n} w_j r_{ij}, \tag{2}$$

where CSI is the total construction safety index of site i, w_j is the weight of the jth attribute, $j = 1, 2, \ldots, n$, and r_{ij} is the rating of the jth attribute at the site i.

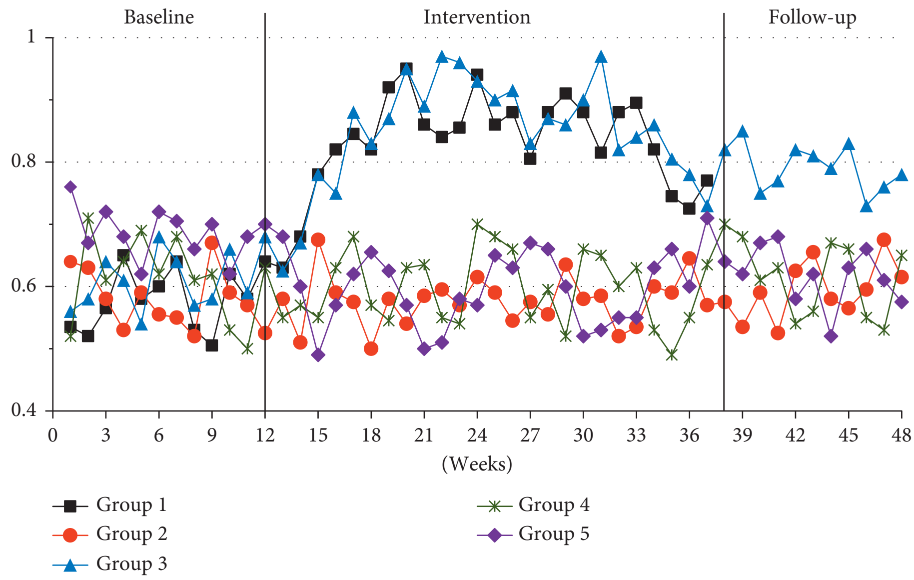


FIGURE 7: Safety evaluation records of two intervention and three control project sites.

5.3. Measurements. To determine how effective the proposed framework is in improving safety management, the five project sites were divided into two intervention groups and three control groups and observed for 48 weeks. Workers in the intervention groups were given coaching sessions by the members of the research team, and the two experts audited the safety management of all project sites every week. For groups 1 and 3, the baseline evaluations of their safety performance were established over the initial 12 weeks. Intervention lasted 26 weeks for group 1, but only 23 weeks for group 3 because by then the construction had finished. Follow-up lasted 10 weeks. Specifically, the proposed management framework in this paper was introduced in detail to the top managers of two intervention groups firstly and received their strong support. Further, the framework was delivered and implemented to all staff on the construction site by ways of supervision meeting and preconstruction clarification. In accordance with the framework, each manager and worker was given a clear responsibility for safety management, and when the safety manager leaves the construction site for some reason, a relatively more experienced temporary safety manager must be appointed to ensure that leadership is always ubiquitous. Meanwhile, within every construction team, considering the gender, age, experience, and skills of each worker and other factors, each two workers were paired and bound according to the complementary principle. During the intervention, they were required to help and supervise each other in their works and be accountable for each other's safety. If one of them is rewarded or punished, the other one receives the same reward or punishment. In contrast, the control group maintains the original safety management framework. The two experts made surprise visits to the sites every week without a predictable schedule. The first expert was responsible for auditing groups 1 and 2, and the second expert for groups 3, 4, and 5.

5.4. Safety Outcomes from Trial Audits. Figure 7 shows the ratings of the five projects sites before and after the intervention. In the three control groups (groups 2, 4, and 5), there were no significant changes, and their CSI scores remained fairly constant over the entire 48 weeks at an average of 0.58, 0.61, and 0.62. For the intervention group 1, the CSI scores went from a baseline of 0.58 to 0.84 during the intervention and to 0.81 at follow-up. For intervention group 3, the CSI scores in the three stages were 0.62, 0.88, and 0.79, respectively. For the two intervention groups, CSI scores increased significantly during follow-up—both individually (39.1% and 28.4% increase) and when combined (33.8%). Therefore, the proposed framework proved to evidently strengthen safety management at construction sites and solve the "last mile" problem.

6. Conclusions and Future Work

In this work, we reviewed and discussed the main factors affecting construction safety from the macro-, meso-, and microlevels. We then defined the "last mile" problem. Subsequently, the human factor was identified to be the leverage point of construction safety management based on a questionnaire survey and statistical analysis, which helps to deepen the understanding of the accident rules on construction sites in China. Further, we proposed a new framework that requires ubiquitous presence of leaders at all times and puts workers into pairs and bands to strengthen safety. The proposed framework was tested in five sections of the Wuhan-Shenzhen highway project and was found effective in enhancing safety management and thus solving the "last mile" problem.

Due to time and cost constraints, the questionnaire survey could not be conducted at a still larger scale. Massive data were obtained through one single survey to which numerous workers provided their responses during their spare time working. This workload made data collection laborious and expensive, although it was indeed essential to secure a reliable input dataset for the sound modeling and analysis of safety performance. In the future, we plan to adopt automatic data acquisition based on the on-line Group Decision System (GDS) to collect related data from international subjects and then analyze the difference in safety cultures and practices across countries and among construction enterprises around the globe.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Review Article

A Bibliometric Review on Risk Management and Building Information Modeling for International Construction

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International construction is complicated and involves high risks. However, with the development of technological innovation, Building Information Modeling (BIM) emerged and seems to be able to address certain risks. To understand BIM applications in risk management for international construction, a state-of-the-art review is required. Therefore, this paper aims to identify the research trends and opportunities for risk management in BIM-enabled international construction by reviewing 526 peer-reviewed journal articles for the years 2007–2017. Thus five steps of bibliometric analysis were conducted based on the proposed frameworks of BIM risk management in international construction (BIM-RM-INTL). The results show that the popularization of BIM not only attracts all stakeholders' interests but also brings some risks. For example, financial factors are hard to detect and control through BIM, information loss during transmission stands out, and BIM has no unified standards and regulations for international construction. The research has mapped existing research results and their relationships for future risk management in BIM-enabled international construction.

1. Introduction

Although Building Information Modeling (BIM) has demonstrated its significance in construction management and being embraced by increasingly and more clients [1], its application remains in the growth stage [2]. However, international constructions are more complicated than domestic construction projects in contractual terms and are also exposed to greater risk such as cross-cultural differences, multistakeholders, and legal and standard differences [3]. Even though BIM has the capability of dealing with complex construction problems and integration of massive information, reviews of BIM in international construction's risk management still is sporadic. Additionally, for international construction, BIM is great software for improving design process and facilitating on-site communication. However, risks at the project's whole life span are more acute and important to solve. In this regard, the risk-management challenge for BIM-enabled international construction demands for studies and practices that can provide solutions to current problems. Therefore, this study defines BIM-RM-INTL field as BIM-enabled international construction using BIM as a tool for risk management, including traditional construction risks, risks caused by international feature, BIM risks, and so on.

Previous studies mostly focused on the research of international construction risk management, such as political risk management on international construction [4], and management-reserve estimation for international construction projects [5]. Some individuals pay attention to the studying BIM technology development and application in the construction industry [6]. BIM is used in construction design process [7] and BIM 3D/4D/5D technology for cost, schedule, and material management [8]. However, there is insufficient research on risk management of international construction using BIM and BIM-enabled international construction risks.

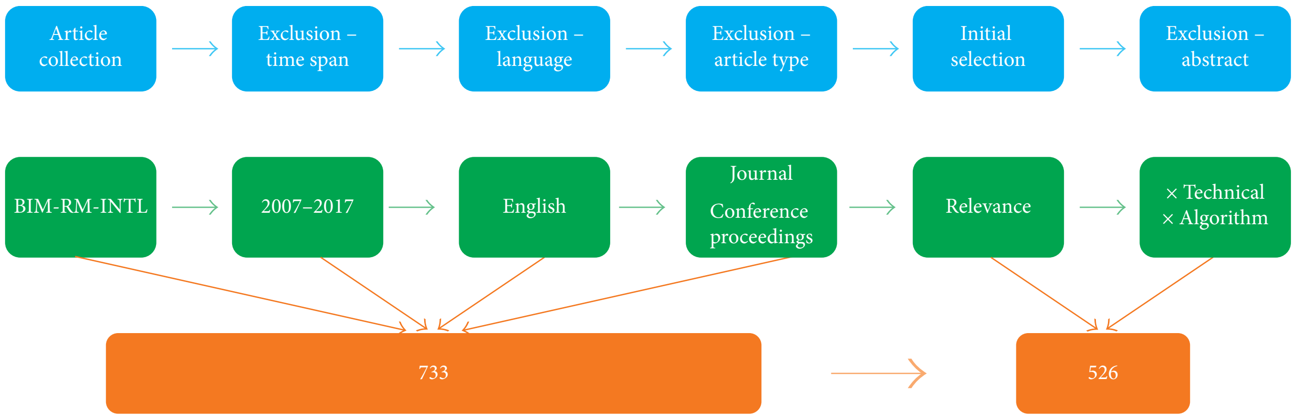

Figure 1: Paper retrieval process.

In order to draw inspiration for future studies that illustrate the gaps and details of current status, this paper aims to (1) collect peer-reviewed articles and conference proceedings in the BIM-RM-INTL field from 2007 to 2017, which could ensure the integrity as well as sufficiency insights into the research area; (2) acquire an overall research status from the perspective of keywords cooccurrence network and time zone network; (3) identify the potential research topics by examining keyword burst detection; (4) analyze the intersections of research groups and patterns through abstract term cluster analysis; and (5) build a framework for BIM-RM-INTL that demonstrates details and gaps of the field so that future researchers can gain a more in-depth understanding of the field. Lastly, based on the studies of Hastak and Shaked [9] and Eadie et al. [10], we proposed a framework that addresses the directions of future studies as a final result of this study. An interview was conducted to fine-tune our findings in this review.

The rest of the paper is structured in the sequence of bibliometric study. Section 2 shows the procedures of this study in detail. Section 3 presents the keyword cooccurrence network that poses the semantic relationships of various research elements, followed by Section 4 in which the keyword time zone analysis displays the past research trends and evolution of research topics over the years. Section 5 shows the burst of keywords and reveals the focus of interdisciplinary fields chronically. Section 6 groups keyword terms into semantic clusters to present relationship of research groups and the intersections. In Section 7, a structural framework is proposed which outlines the distributions of to-be-explored areas as reference for future studies. Finally, Section 8 concludes with the findings and limitations of this study.

2. Research Methodology

2.1. Paper Retrieval. In this study, Web of Science (Clarivate Analytic (2017) *Web of Science Fact Book*. Retrieved May 27, 2017, from: http://clarivate.com/scientific-and-academic-research/research-discovery/web-of-science/) datasets of bibliometric analysis and journals concerning risk management of international construction using BIM were identified and gathered. The paper resources collected from the database are sufficient and highly reliable since papers were picked out after rounds of strict peer-evaluation and selection. Additionally, the abundant quantity of qualified academic papers is adequate to represent the main body of the BIM-RM-INTL field of study.

Considering the probability of downloading unrelated papers or papers with little relevance, it is necessary to eliminate unwanted ones. By reading the abstracts carefully and analyzing the problems articles aim to solve, 526 journals that conform to the criterion were selected. The criterion is described as below. Figure 1 shows the framework of paper retrieval process.

First, three sets of keyword terms were used to triangulate the articles related to risk management, BIM-enabled projects, and international construction. The search strategy was triangulating *("BIM" OR "Building Information Modeling" OR "Building Information Model" OR "Building Information Modeling") AND (risk OR safety) AND (international OR global OR world) AND management*. Then, only journals and some conference papers in English during 2007 to 2017 were saved. Since studies of construction field strongly rely on practice, though study quality is guaranteed in journal alone, may not be in accordance with practice or in the frontier of the field. Furthermore, management methods' implementation and experiences are often communicated in conferences. Thus, some conference papers were included in this study. Since BIM technology, which is what this paper meant to focus on, has only been put into large-scale use within the last decade, previous studies and practices are scarce and of little help. Accordingly, the time span was restricted to 2007–2017. To incorporate high quality into international construction and cross-country findings, this study chose English, the universal language, as the only language papers should be in.

Second, to avoid containing irrelevant papers with titles concerning BIM-RM-INTL in the database, for example, grid construction and biology technology are not relevant but might contain the same term, these journals were eliminated by checking the content of papers through skimming their titles. Then, by reading the remaining abstracts, papers about purely technical issues, such as those solely about the development of software, BIM technology optimization, and risk analysis algorithm, which are not relevant to management field, were deleted.

Since the data analysis implemented in this study relied on title, abstract, and keywords of the paper, the methodology, emphasis of research field, and findings were all included. With the precision of information extracted, the result was high accuracy. According to the criterion above, 526 papers were picked out, and 733 papers were deleted. The selected 526 papers are published in major journals and from international conferences. Figure 2 shows the citation details of the distribution of the 526 bibliographic records from 2007–2017.

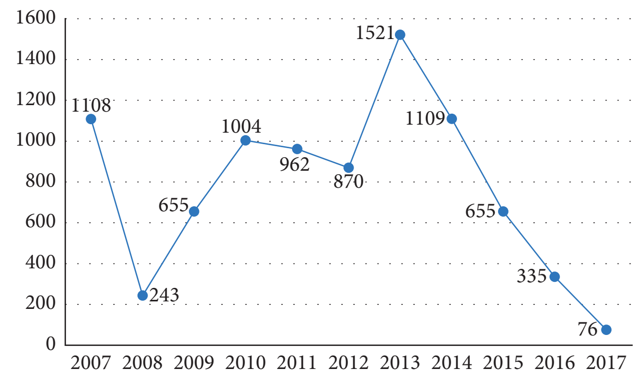

Figure 2: The citation details of the 526 papers in 2007–2017.

2.2. Bibliometric Analysis. Understanding the earlier studies and the trend requires analyzing big amount of paper, extracting information, and building conceptual framework. However, manually reviewing papers at huge quantity is impractical; meanwhile, subjective categorization and clustering are prone to human-related systematic errors or false analysis. Bibliometric approach, functioned by automatic calculation, can remedy this situation. Bibliometric approach is a method that integrates the information of large-scale data; by scientific calculation, it can then map the structure and evolution of knowledge in the database. Through visualizing the results, the relationship of study fields can be easily grasped. The landscape of researches' abundant or rare resources can be depicted clearly. Bibliometric approach helps to outline the framework of current BIM-RM-INTL field of study.

The research area this study examined contains interdisciplinary knowledge as well as large number of specific studies in only one field. BIM technology as a multidimension tool provides great convenience to construction enterprises so that scholars worldwide are studying its function and implementation. Risk management in the construction industry, where the money involved is usually very big amount, is very important for controlling the quality of buildings and ensuring the profits. Many studies have placed emphasis on risk identification and control system. Research on international construction is prevalent with the spread of globalization, and it is becoming more important in China since more enterprises are walking out of mainland China to find opportunities in other countries. Manually analyzing these three fields and their intersection is not practical since the papers and knowledge included are of huge-scale. To better understand the research status of these three fields at the base of large-scale papers extracted, this paper adopted CiteSpace [11] as the tool for analysis. This software was used for links and network building and analysis as well as mapping visualization. All the information was extracted from terms in keywords and abstracts that the authors wrote to summarize their studies.

A publication's keywords and abstracts are what the author considered capable to represent the study. Thus, using terms from keywords and abstracts as analysis units can represent the research framework of BIM-RM-INTL field. Keyword cooccurrence analysis, keyword time zone analysis, keyword burst analysis, and abstract term cluster analysis were adopted in this study to demonstrate research patterns and past trends in BIM-RM-INTL field.

First, keyword cooccurrence analysis based on the mapping results illustrated the network of BIM-RM-INTL field; the links among words represent connection of researches and provide evidence for further cluster analysis. Second, keyword time zone analysis demonstrated the evolution of researches by showing connection lines colored by year and its transition, and highlighting the hotspots in different years. Third, keyword burst analysis gave insight into individual term's strength through the time span, which could provide more specific evidence to time zone analysis and suggest different opinions. Finally, cluster analysis provided evidence about grouping of research patterns and intersections, which allowed framework building accordingly.

Mean silhouette value measures the homogeneity of clusters while modularity Q represents the strength among node links. High mean silhouette value indicates strong homogeneity inside a cluster. High-modularity Q value stands for dense connections between nodes within modules and sparse connections between nodes in different modules. A convincing semantic mapping requires mean silhouette value to reach 0.7 [12] and modularity Q to 0.3 [13]. This would be the criterion for the credibility of figures in this study.

3. Keyword Cooccurrence Analysis

The keyword cooccurrence network is demonstrated as Figure 3. The overall network shows the research centrality and edges as well as the evolution of researchers' concerns through time. Nodes in the map stand for terms that can represent one of the basic concepts of each article. The radius and color of each node demonstrate the link strength of it in each year. Most frequently linked nodes were tagged by the representing word. Lines that connect nodes indicate the year that the two words first being used together in one article. The line weight indicates the link strength through years. The thicker the link, the stronger the relationship. The color of both nodes and lines, in all, clarifies the old and new areas in this field of study. Color transition from cool tone to warm tone signifies the time span from past to present.

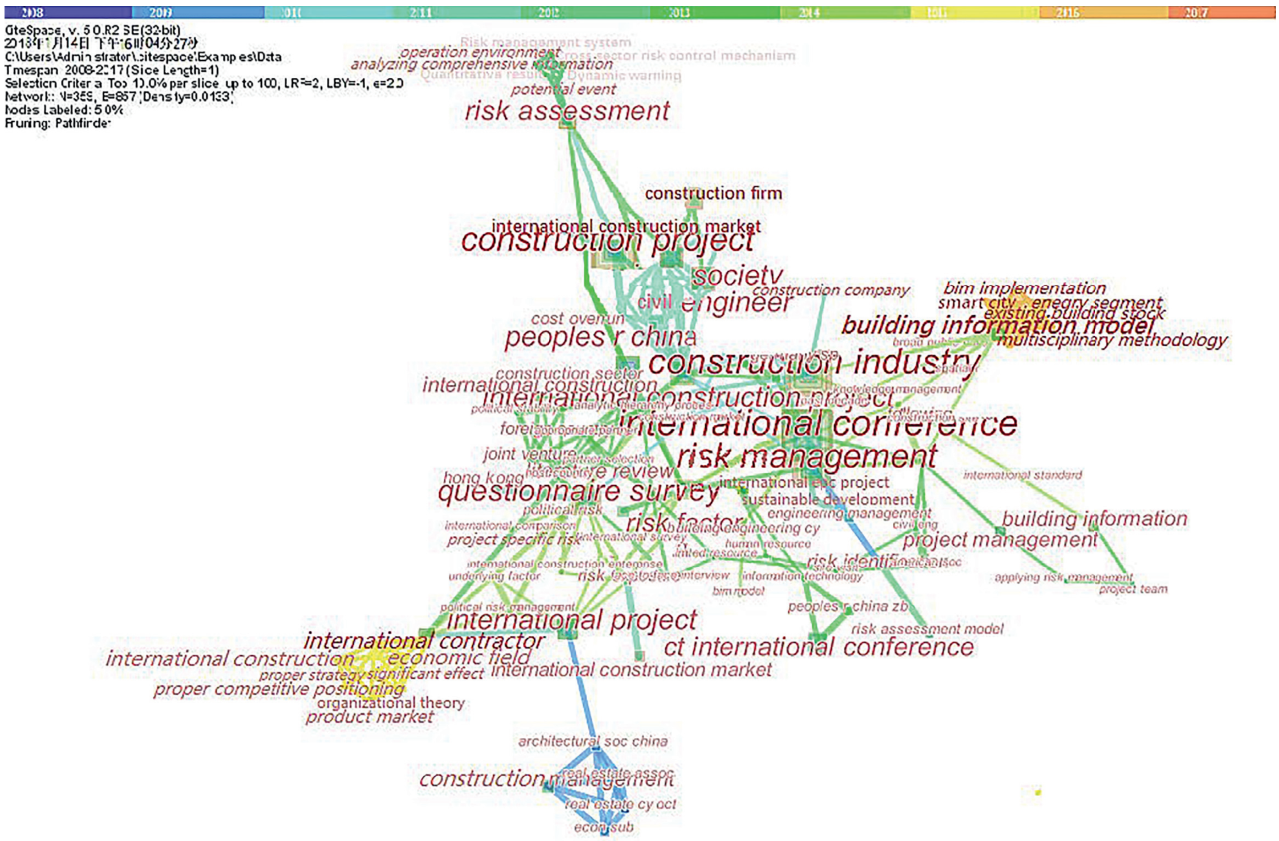

Figure 3: Keyword cooccurrence networks.

As the selection criterion went as "10.0% per slice (one slice equals to one year), up to 100," Figure 3 shows the very detailed mapping of BIM-RM-INTL field of knowledge. Although this figure can delicately demonstrate the relationships among different concepts, it shows that the silhouette value, 0.1945, did not reach the standard for cluster analysis, which will be applied in Section 6. Thus, to create a more convincing mapping for cluster analysis, this study narrowed down the percentage terms that were extracted for the use of analysis to 1.0%. As shown in Figure 3, modularity Q (0.6354) and mean silhouette (0.7005) both reached the standard. However, there is a price to take—lack of content in the mapping. Thus, in order to take advantage of both figures, this study adopts Figure 3 for keyword cooccurrence analysis, seeking detailed link analysis and adopts Figure 4 for further cluster analysis, ensuring the accuracy of results.

BIM, comparing to traditional construction project and risk management, is a new field of study, and studies about BIM are new-rising as well. Though the concept was mentioned at late 70s and has been put into use for years, the low popularity, high qualification, and immature standards made this field still thriving. China imported BIM technology since 2003 [14], but no law or professional standard has been established to date. BIM could bring instant benefits to all parties concerned in a project [15]. Since the implementation of BIM technology and construction policies concerning BIM are both at early stages, educational programs designed for preparing skilled BIM students or workers are evolving [16]. Training of professionals could clear barriers through BIM implementation and improve the abilities of professionals [17]. Advantages of BIM have been studied thoroughly, and the instant benefits contractors experienced have been categorized in detail [18]. The process of facilitating BIM adoption and the latent challenges are being reciprocally studied through years [19, 20]. In practice, enterprises intend to advance implementation theories so as to use BIM-based tools to its full gear, which advances the project's functionality [21]. While some features of BIM can help solve project risk, it is not possible to conduct comprehensive risk management.

Culture poses a salient concept in keyword cooccurrence network since variation in value system and transaction practices normally serve as the barriers of project delivery [22]. To better accomplish projects in international construction, one must understand the cultural background. Different cultures might have different acceptance towards new technology, and different attitudes and habits in dealing with people and participating in projects [23]. Immature cooperation culture might lead to difficulties to life cycle BIM implementation as well [24]. Stakeholders may resist sharing information, particularly costing or scheduling information that may be used against their liability in breaching the contract. Project managers' lack of knowledge in BIM leads to low efficiency in BIM implementation as well as the lack of competencies in job field personally [1]. If stakeholders overlook the variations in regulations, they might encounter troubles in building process.

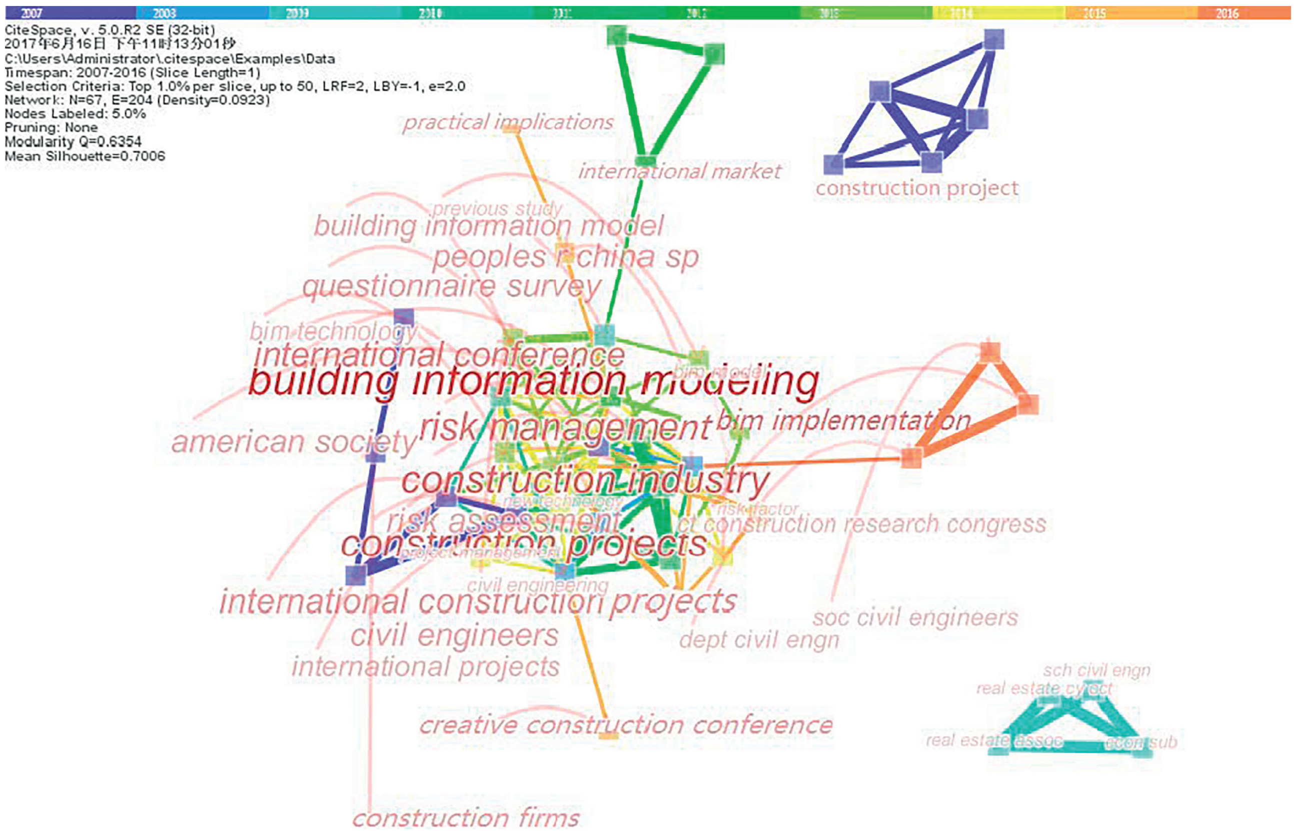

Figure 4: (Extracted) keyword cooccurrence networks.

In the international sector, "political issue" has strong link with it. Political issue is a key factor in which the project can be carried out successfully since international construction is very social stability. Partner selection, on the other hand, concerns subjectively choosing partners. Proper choice of local joint venture partner plays an important role in reducing political visibility [25]. Reliable stakeholders can help conduct the project better in a foreign country for the firm but the opposite case might have negative impact on progress [26].

Different from partners, international contractor means an aspect related to law and new ways of risk allocation [27]. Business issues, including marketing, proper strategy, and proper competitive positioning are included [28].

It could be easily determined that the most popular method of analyzing risks is questionnaire survey. It can be used in deciding risk factors [29], risk impacts [30], international construction comparison [31], and so on. Since the construction industry relies heavily on practices, by choosing experienced experts through scientific approaches, deciding risk categories and their impacts by expert interview is the most reliable. Researches about risk exposure are about to mitigate negative impact by knowing under what circumstances the constructions are prone to risks most likely to happen [32]. By reducing such situations, risks can be avoided or reduced. Risk assessment, which is conducted throughout a project, greatly influences the process and outcome. Different risks, concerning cost, social issues, asset, and social environment, are being considered in great amount of papers. Risk management methods like dynamic analysis [33], quantitative risk assessment model [34], and fuzzy theory [35, 36] are being studied.

Risk assessment part is separated from risk management in Figure 4, which is not same as how our conceptual framework works. The reason can be that assessment process focuses more on dividing construction phases and give in-depth study about each stage and aspect of a project instead of being integrated in risk management field.

4. Keyword Time Zone Analysis

Keyword cooccurrence network is a static figure even though initial year of links between words is represented by different colors. Time zone analysis arranges terms in a chronological manner that shows the trends and interactions among keywords. As shown in Figure 5, the colors of these lines are showed when a connection has been made for the first time, and the lines that connect nodes are cooccurrence links between different keywords. According to the complete result shown in the software, this paper did insight investigations.

In 2007, the main research focus on concepts relating to "risk assessment," "risk management," "international construction projects," "risk factor," and so on. It could be seen on the figure that in 2012, with the rise of BIM technology, the field of civil engineering and risk management started to establish links with BIM. Since BIM technology integrates information in a nD model (nD model means all the

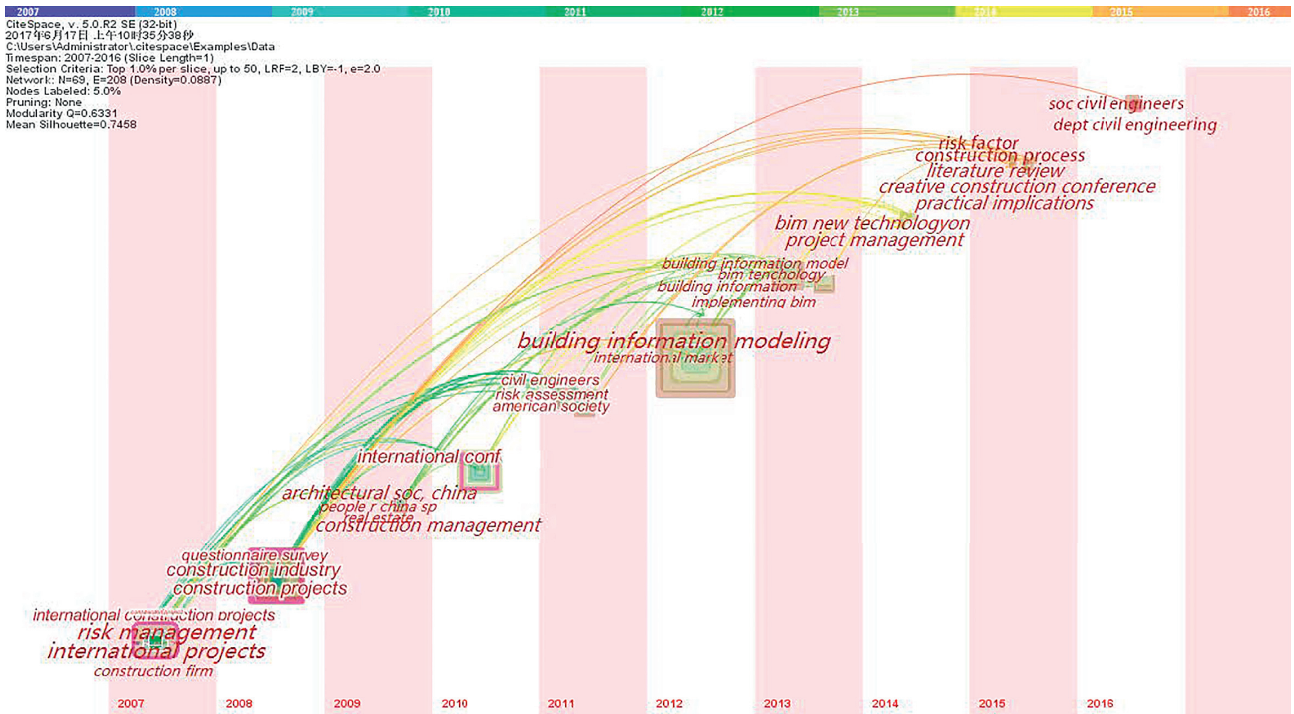

Figure 5: Time zone.

dimensions of BIM technology, e.g., 2D, 3D, 4D, 5D, 6D, . . .) [37], for risk management which requires detailed information in every stage, BIM stands as a future processor for risk management [38]. This link demonstrates their relationship. Sustainable development, involving the demolition and refurbishment of buildings as well as green building and so on, emerged in 2014. As a new practice, in order to assess the risks and possible barriers, a lot of risk management issues and information management methods were discussed [39]. BIM also played an important role in developing sustainable building. 2015 is an important year of risk management studies. Theoretical research about risk assessment, identification, and others established strong links with practical implication, especially for risks that are more subjective and related to human reasons [40]. As such, fuzzy approach was widely adopted for semantic analysis on human factors in risk management [41]. Furthermore, international constructions also had strong links with it. The studies about integration of BIM, international projects, and risk management involved practical uses. For instance, asset management through knowledge management was broken down to issues like liability, authenticity of BIM users, and development of new ways of collaborations for practical instructions. The usage of BIM started to be expanded in 2015 when project cost, in-depth design, and safety issues were widely discussed, and all of them were closely connected to BIM [39]. Researchers have been relating topics like spatial conflicts and site safety management to BIM. In 2016, BIM started to be integrated with risk management in a project's life cycle [42]. PMBOK breaks down risk management into three phases: risk identification, risk analysis, and risk management [43]. A project's life cycle has been separated into design, construction, operation, and demolition. Secondary phases have been identified as well. The relationship between risk management stages and construction project's life cycle is being studied. For example, during the operation stage, existing modelling conditions which involve laser scanning, image, and data processing have been deployed to manage the construction quality (its risk intervention phase) [44]; in the design stage, BIM can provide detailed data for optimization of management resources, for example: it helps quantity take-off, project cost estimation, information records of spare parts, labour, and machinery (it's risk identification and intervention phase) [45]; to reduce safety risk, BIM can provide a virtual construction platform and safety simulation environment so as to enable all the parties to develop a better construction safety plan (it's risk identification and intervention phase) [46], and so on.

5. Keyword Burst Analysis

Time zone analysis gives insights into trends and evolution of researchers' interests, but still it is unable to explain the centrality of words. Keyword burst analysis, accordingly, stands out to indicate words, which possess impressing link strength, its centrality, and active years. These words stand out to be representative of particular fields of study so that the performance of them can display attraction towards researchers during a certain period of time. However, there are words that cover too big the scale that they lack the ability to certain statements or similar terms were identified in the same figure. In Figure 6, *international construction projects*, *civil engineers*, *building information modeling*, and *BIM*

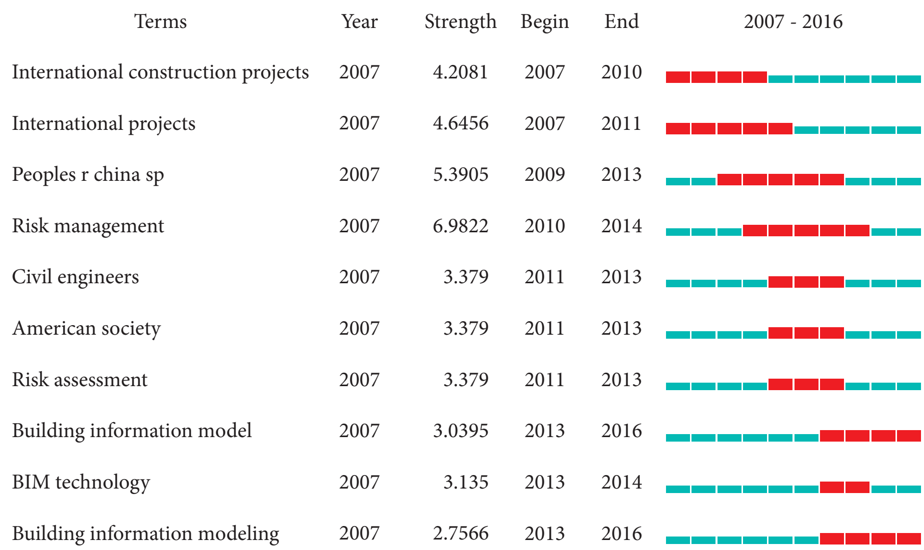

Figure 6: Keyword burst 2007–2016.

technology are the foundation of the study, on which the research structure was built. Different researchers are using different terminologies in their papers. For example, international projects are described as "international construction project" or "international project," respectively. BIM terminology also appears as "building information model," "BIM technology," or "building information modeling," so in the keywords burst results, these terms are duplicated.

(i) "International construction projects" and "International projects" as a prevalent concept due to the internationalization progress remained popular during 2007 to 2011. In the past 30 years, with the development of economy, many countries began to build international construction projects. According to ENR THE TOP 250 data, international engineering contractor revenue $310.3 billion in 2007 increased to 544.3 billion in 2014. With the increase of international constructions, the research on international constructions has gradually increased. Therefore, during this time, international constructions were being widely studied.

(ii) "Peoples r China sp" is the abbreviation of "People's republic of China" in CiteSpace, whose frequency could be related to studies by Chinese researchers. As an important emerging country, whose construction field is thriving rapidly, its importance burst out was in 2009–2013. During this time, papers published by Chinese researchers were abundant, and the amount of case studies based on Chinese practices is huge [47]. Since 1997, China has been putting the national strategy—*Go Globally*—into practice. However, at that time, Chinese construction industry was not well developed, and there's a great gap between Chinese and the global standard of construction projects' quality [48]. Since the great development in the real estate field, Chinese construction companies start to expand internationally. Along with it is the burst of researches in this field. It is clear that, in the construction field, China is becoming an increasingly important figure.

(iii) Risk management: risk management has undergone decades of development, but due to the prevalence of risks and the specialization of risk management in the industry, this topic has become popular in recent years. Risk management includes risk identification and risk assessment process, through which risk management can increase the probability and impact of opportunities, while decreasing the probability and impact of the threats to the projects.

(iv) Civil engineering is the main research field of international construction and BIM, so these topics are inseparable with development in civil engineering.

(v) As a pioneer in new technology and management fields, the US' cases are being widely studied and imitated around the world. Experiences of implementing BIM, including the problems teams encountered as well as the benefits, are of high value for other construction projects [49]. The regulations, culture, and atmosphere of *American society* have caught researchers' attention for better understanding how projects have worked with a certain background. At the same time, how organizations adjusted to the advancement of technology is important for future projects [23]. By studying American's cases and analyzing similarities and differences between social statuses, one could better conduct projects with new approaches in his own country.

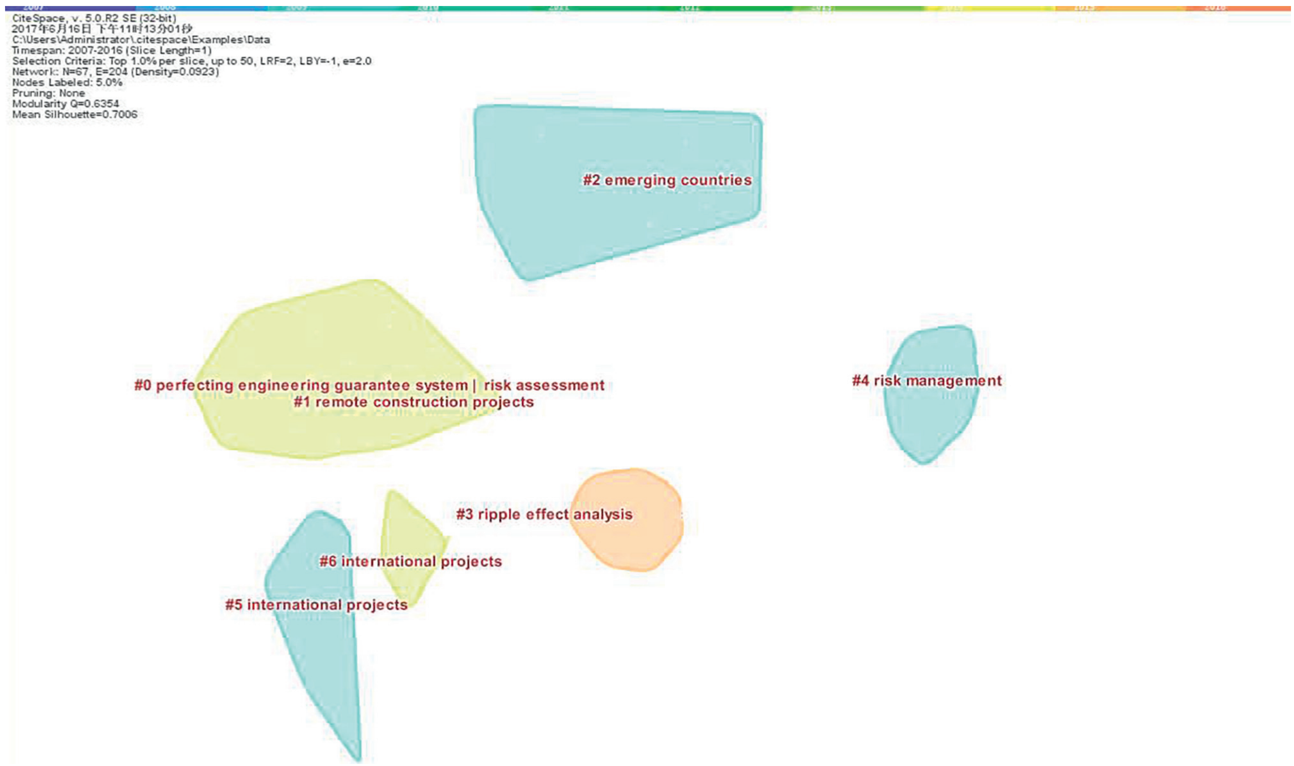

Figure 7: Cluster map.

6. Cluster Analysis

Scrutinizing the information keywords could bring is essential for understanding the trend of BIM-RM-INTL field. However, keywords are too detailed and sporadic to clarify major areas and research structures. Cluster analysis, through mathematical and statistical calculation of text data (which was refined to keywords and abstracts in this study), is able to summarize the latent semantic themes and their overlaps [50]. Through multidimensional cluster analysis to investigate merge concepts with strong inner relation, researchers could understand the prevalent thoughts in the field and its frontier. Cluster analysis employs a set of algorithms to attraction and repulsion of word links and then terms the cluster groups. Each cluster reserves and represents a certain amount of the overall observed terms [51].

CiteSpace allows researchers to decide what kind of algorithm they would like to use to name the clusters. For instance, name by the term of highest frequency or highest centrality. To fully understand the cluster and its implication of connection among groups, this study adopts three naming regulations: by highest term frequency; log-likelihood ratio; and mutual information. Figure 7 shows clusters that are numbered in descending order of cluster size and that the naming of clusters is done automatically by CiteSpace default calculation.

6.1. Cluster 0: Perfecting Engineering Guarantee System—Risk Assessment. Engineering guarantee is often seen in ensuring project's schedule and contract behaviors. The construction of this system can better integrate credit system, financial security, and project management by importing a third party. This technique was firstly used in developed countries, which was imitated and expanded in other countries nowadays. This cluster is closely connected to *International Projects* and *Emerging Countries*, which indicates the importance of it in construction delivery and the in-depth research developing countries have on it. International project general FIDIC contract is also a regulation to guarantee clause

Risk assessment is aimed for the uncertainties at different stages from different aspects and their impact on international construction. Through the risk assessment, result can undertake preventive measures and guarantee the project process.

6.2. Cluster 1: Remote Construction Projects. This cluster shows the management of international construction using BIM; this could be proved by the closeness between it and *International Projects*. Remote construction project is based on the development of information technology and Internet building so that supervision and management in homeland country become available. Due to the digital feature of BIM technology, design process, construction progress, safety management, and other issues became possible. Using BIM to supervise construction could ensure that the project goes as planned and the ability to grasp the construction drawbacks and quality defects. Efficiency and quality of international construction are promoted.

6.3. Cluster 2: Emerging Countries. As the main body of construction field, emerging countries are very important to BIM-RM-INTL, and they are supposed to be the pusher of

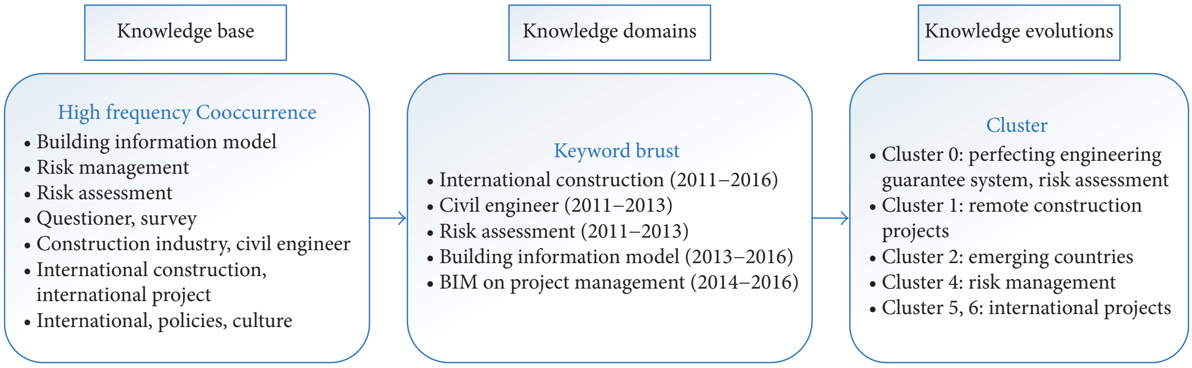

Figure 8: BIM-RM-INTL current research map.

development and practitioners of new technologies. Thus, from the figure, we can see that *Emerging Countries* appears as a sole cluster, and its position is very close to *Risk Assessment* and *Remote Construction Projects*, which indicates the relationship among them. In countries where construction field is well developed, they would choose to construct in other countries so that the productivity actually shifted. Nowadays, more and more engineers in emerging countries are supposed to receive trainings about new technologies and possess the ability to use them. Educated engineers could have the capability of integrating new technologies and the process of project management so that the sudden barriers brought out by implementation of BIM could be diminished [20].

6.4. Cluster 3: Ripple Effect Analysis. Ripple effect analysis is mainly used for complex information models. From researches in 80s analyzing the maintenance of information models [52] to developing the ability of BIM to analyze and predict the effect on whole of a small change in factors nowadays [53], ripple effect analysis is the foundation for information systems. At the location where it is near *International Projects*, *Risk Management*, and *Remote Construction Projects*, it is easy to see the importance of BIM in BIM-RM-INTL field [21].

6.5. Cluster 4: Risk Management. Risk management is a grand field; PMBOK separates it into a few steps: risk identification, risk analysis, and risk management. According to our search strategy, risk management should have close relation to construction projects. Nevertheless, from Figure 7, risk management is very far from BIM and international construction. Meanwhile, risk assessment includes risk identification, and when it is separated from risk management, it becomes an independent cluster, which has intimate relationship with international construction and information technologies. For risk management, choosing partners and contractors at bidding phase, as well as changing the positioning of a project, is so important that researchers put great efforts on this topic [54]. Investigation on risk analysis and risk intervention is a sole group; further research could put emphasis on connecting it with international construction practices.

6.6. Clusters 5 and 6: International Projects. The abundant knowledge and wide range of international projects made it two clusters. Due to the limitation of CiteSpace function, we cannot identify the differences between these two. Thus, this study considers them one big cluster.

One of the features of international projects is remote construction; this has already been discussed in Cluster #1. International projects also have close connection with ripple effect analysis, which proves that informational control is also important for international projects. The global feature of this cluster made the content colorful. Some major problems, like market entry modes and how to cope with political changes, are being widely discussed by researchers. In the bidding process, fragile parts in international construction should be considered in prior to other factors [55].

7. Framework Development and Discussion

The framework is used to identify research gaps in current studies. First, based on the bibliometric approach, results establish the BIM-RM-INTL current research map, shown in Figure 8.

BIM, international construction, and risk management have separate research. For development of the future framework of BIM-RM-INTL, in this paper, analysis of the research topics is given in details.

In risk management, there are lot of researchers who have used methods such as the hierarchy risk tree and expert interview to conduct risk identification and categorization. Traditional international construction risks fall into three levels: macro (nation-wide), market, and projects according to Hastak and Shaked [9] research. More detailed risks, like economics, scheduling, quality, and safety, were listed in the inferior level. Liu et al. [56] and Zhao et al. [57] identified risks on international construction, particularly on macroeconomics risks, social risks, political risks, legal risks, contract problems, client-related risks, design problem, safety risks, procedure complexity, technical problems, material and equipment problems, project team risks, and cost overrun risks [6]. In this paper, through the literature, analysis identifies the most common risks in international construction. The political risks, legal risks, social cultural risks, economic (cost) risks, management risks, technical risks, partners' risks, and contract risks are also highly

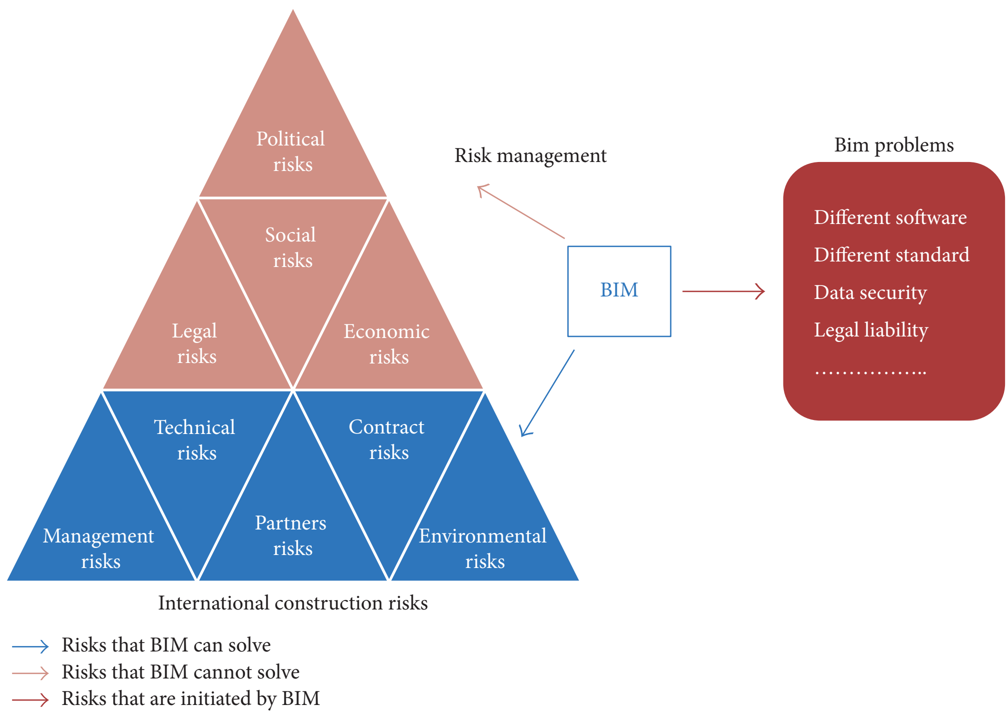

Figure 9: The proposed framework for future studies in BIM-RM-INTL.

mentioned by the academic publications for international construction risks.

BIM is a new development technology in construction industry, as shown in Figure 5. BIM function of 3D–5D can be used for design and construction stage. In design stage, BIM 3D can check collision, solve the conflict of spatial relations and design errors, and also optimize the design steps [58]. In construction stage, BIM is able to provide information, schedule and cost and bill of quantities for construction simultaneously. For minimizing risks of improper planning and cost overrun risks, a 5D automated cost-estimating model has been developed to provide a more accurate cash flow forecast that allows stakeholders make appropriate decisions for different design and payment scheme alternatives in construction projects. 4D can intuitively reflect the construction interface and construction sequence. Thus, the construction coordination between the contractor and the professional construction company becomes clear and it functions in analyzing the workplace [59]. Especially, safety control technologies like laser detection and potential danger prediction by BIM have been developed and put into use. The schedule is normally being updated through the construction process; the merge of Microsoft Project (or other scheduling document formats) and BIM is quite prevalent nowadays. The performance of quality control, hard to count and hard to deal with practically, in BIM is limited to possible defects prediction. Interoperability among different software and information flow control is experimented to be controlled by BIM. However, different standards of software in different countries are beyond the reach.

Since various factors, which are too vague to be quantified, may influence the administration decisions and communication, it is not possible to use digital analysis. On the global scale, common international construction risks that take political status, economic stability, and social cultural differences into consideration are even harder to quantify. Political status is unpredictable and its effect on social stability is huge. Economic unison, which could be understood as steady exchange rate and acceptable inflation, is hard to predict as well. Economic factors are prone to political changes, not just within the country but also the relationship of the local country with others. Social factors are also so subtle that differences in the way people behave and think in social activities are impossible to be fully concluded. Social scientists are still working very hard on cross-culture communication, not to mention quantifying it into a building model by using methods such as the fuzzy approach. Thus, the international risks require more intelligence in assessing the social environment and investment risks, not technological interference.

As discussed above, new technology could bring new problems to life, as shown in Figure 9. In order to prevent vicious cycle due to the lack of ability to control risks, this study suggests the current research status and future possible topics in a framework. Though bibliometric approach could provide insights into the current research area, it might have differences with the real life experiences since some problems in practice are not listed and the theoretical conclusions might not apply. Thus, in order to keep the results of this study accurate, we interviewed a few experts in this field to check the findings. These experts are contractors for international highway projects, and they have extensive experience in international project and have been advocating the implementation of BIM management for many years. Interviewed experts include the chief executive of BIM who has 7–12 years of working experience. BIM software development company, the main researcher, has 10 years of work experience. The college professor who has mainly studied and implemented the BIM project has 15 years of experience. Through the interview, we got to know some important risks that bibliometric did not present: (1) network at construction site is very poor, the interaction of information is very untimely, and the process of remote control is very challenging; (2) renting of facilities is complicated, but buying new facilities costs too much money to cover; (3) constant supervision is not practical for home contractor and it's hard to control construction quality; and (4) though watch dogs have been installed, since the current technology cannot directly extract information of safety behaviors through video, contractor still needs people to do the task and BIM's performance has not been in full use. Meanwhile, many conclusions discovered by bibliometric approach have been proved: since the popularization of BIM concerns interests of all stakeholders, some management issues could not function as planned. For example, contractors or subcontractors will not put construction defects into BIM since it might influence the possibility of compensation; financial factors are hard to detect and be controlled by BIM and contracting is still the most important way to control this risk; information loss during transmission stands out and this situation deteriorates when construction groups changes frequently; and only few countries have built up BIM models with their standard and regulation implemented and it's hard to conduct BIM building in most countries due to the variety of building standards, and so on.

Current studies include the following concepts: life cycle risk management is put into BIM to better gain control of it [37]; remote construction projects have been suggested for construction enterprises who have strong administration in home country or are concerned in design disputes; and through the interview, we can also can know new risks brought up by BIM implementation, since not sufficient examples existing, could only be estimated by experts or experienced professionals, and the risk could be possibly underestimated. The concept of smart city has been studied and the integration of construction, transportation, landscape, and others elements underway [60].

Future BIM-related problems would be based on how to better conduct construction works in different places that have different standards by BIM. Different construction approaches could be demonstrated by BIM on how to standardize modeling methods among different groups or countries and how to precise BIM-enabled international projects risks. These topics may require further study later. To help international contractors, apply BIM technology in controlling and preventing risks.

8. Conclusion

This article was based on 526 papers collected from Web of Science, that are related to BIM-RM-INTL. The papers were limited to those written in English and published during 2007 to 2017 in journals or from conferences in order to cover all possible directions as well as confirming the quality and relevance of papers to the best. A series of bibliometric approaches was adopted to analyze the development track and trend in this overlapping field. The title, keywords, and abstract were used to represent the research. They were analyzed in terms of keyword cooccurrence, time zone leaps, and frequency strength of keywords and semantic grouping of abstract terms. First, the keywords were determined to construct a static network that indicates interrelationships among concepts. Second, cooccurrence of keywords demonstrated on a time span clarified the changes in study interest chronically. Lastly, the abstract term analysis revealed seven groups that represent research themes.

Regarding the theoretical contribution, this article has identified risks on international construction. By scrutinizing the risks and BIM risk management of their characteristics, this article built up a framework, which shows in figure current research field, and suggests future research directions. Traditional risk analysis, international construction analysis, and BIM implementation analysis put much focus on experience and practical problems that the research individual has observed. This paper has mapped existing research results and their relationships, which can be used as an indicator of possible research area as well as instructor towards problem solving. The collection of papers and scientific algorithm ensure the accuracy of the representation of previous works and reliability of the framework.

Regarding the practical contribution, many conclusions made by bibliometric approach have been proven: the legal system and standards in each country is different which in a BIM-enabled international project can easily lead to conflicting information and information loss risk hence affecting project collaboration. Therefore, the framework, a possible topic, "How to better conduct construction works in different places that have different standards by BIM" is an important problem in the actual project. Since the popularization of BIM concerns interests of all stakeholders, some management issues could not function as planned. For example, contractors or subcontractors will not put construction defects into BIM since it might influence the possibility of compensation. In addition, construction enterprises can effectively use the functions of BIM to reduce project risk.

This article has certain limitations. There may be some other articles in other academic databases that we did not consider in this study. Moreover, the proposed research framework was only developed from a conceptual point of view according to the bibliometric analysis. The framework should be further analyzed and validated with empirical data from a quantitative point of view, especially on how risks impact project goals, and how precisely BIM enabled international projects risks and construction goals. Nevertheless, this study has mapped the relationships between existing research and future needs for risk management in BIM-enabled international construction based on the high-quality database. The results also provide insful implications for both industry and academia.

Disclosure

The authors declare that they have no financial and personal relationship with anyone or any entity whose interest could positively or negatively influence the content of this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Effect of Organizational Cultural Differences and Mutual Trust on Contract Management of Nonequity Construction Project Alliances

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This study aims to examine the impact of organizational cultural difference and mutual trust on the contract management of nonequity project alliances in the construction industry. A questionnaire survey was conducted to collect the quantitative data for this study. The relationships between the variables were analyzed using hierarchical regression analysis. It was found that the contractual complexity of nonequity project alliances was impacted by the differences in management style, differences in organizational responsiveness, mutual goodwill trust, and mutual competence trust. It was also found that the relationship between differences in organizational responsiveness and contractual complexity was moderated by mutual goodwill trust. The research may provide theoretical basis for the management when making decisions on the selection of project alliance partners and contracts. The findings imply that when the firms seek to form project alliances, they need to recognize the level of organizational cultural differences and then determine the proper contractual complexity of the project alliance. In addition, the establishment of mutual goodwill trust between alliance partners will not only reduce the costs of making contracts but also the costs of implementing the contracts.

1. Introduction

The construction project relies on a high proportion of small- and medium-sized enterprises which are involved in off-site manufacturing (e.g., design and procurement) and on-site production (e.g., assembly and supporting services) [1]. Higher number of market participants tends to increase transaction costs and reduce management efficiency [2]. In the meantime, increasingly more construction companies were involved in alliances (e.g., the alliances of client, design, and construction companies) to deal with increasingly intense market competition, complex construction technologies and diversified client requirements [3]. An alliance is a form of relationship contracting in which the establishment and management of relationships between partners may remove barriers and maximize partners contributions and success [4]. Cobianchi [5] found that the success of alliances is positively related to the geographical, cultural, and environmental similarity of the project alliance participants. Negligence of the participants' organizational cultural differences is one of the most frequently cited causes of the failure of alliances (e.g., [3, 6]).

Some researchers argued that proper modes of contract management can be used to balance the benefits of participants, maximize the chance of success for project, and improve the performance of project [7–9]. In general, project alliances are divided into equity alliances and nonequity alliances [10, 11]. Nonequity alliances, which do not involve share proportion relations, are more popular in the construction project than equity alliances. The collaboration of nonequity alliance partners is mainly reflected by the alliance contract, which specifies the scope of collaboration, the rights and obligations of partners, and the way of resolving disputes [12]. Reuer and Ariño [12] further argued that more complex negotiation and enforcing contracts may be avoided when the risk of opportunistic behaviors decrease. Contractual complexity can be used to reflect the degree of cooperation between alliance partners and the degree of constraints applied to the behaviors of alliance partners as the contractual contents include the terms of conditions and coordination [13].

Rodriguez [14] indicated that the alliance partners need to adjust their organizational cultures or cultivate a common culture to improve alliance performance. When there are significant cultural differences, most firms tend to choose integration of partners rather than nonequity alliances [15]. For the nonequity alliances which are popular in the construction industry, it is still unclear whether the cultural differences will have impact on the contractual complexity of an alliance.

Furthermore, China appears to be a country of low credit. However, it has been found that high-level trust exists among families, acquaintances, and friends in the Chinese society. "GuanXi," which describes relationships that may result in the exchanges of favors or "connections" that are beneficial for the parties involved, is an important characteristic of the Chinese business environment [16]. When forming the alliances, the selection of partners is not strictly based on the assessment of a large number of potential partners according to the targets of the alliance, but rather directly targets some particular organizations with "GuanXi." "GuanXi" is embodied in the trust between members of the alliance. The trust of cooperative partners may, to some extent, reduce the transaction risks of the partners and influence the choice of alliance contracts [17]. The traditional evaluation of trust is based on single-sided judgement and reflects single-sided willingness [18]. However, if both parties have different evaluations on trust, the traditional evaluation may not be able to reflect the impact of trust on the performance and risks of alliances. Thus, it seems necessary to develop the mutual trust, which represents both parties' mutual judgement on the alliance organizational trust [18]. Das and Teng [19, 20] pointed out that the goodwill trust and competence trust are the two independent dimensions of trust. Therefore, the mutual trust in the context of Chinese society is classified into mutual goodwill trust and mutual competence trust. This study aims to investigate the interactive effects of the two types of mutual trust and cultural differences on the contractual complexity of construction alliances.

2. Theoretical Background and Hypotheses

2.1. Organizational Cultural Differences and Contractual Complexity. Organizational culture consists of two aspects: (1) management style and (2) organizational response [15]. Management style comprises the management attitudes towards risks and their methods of decision making, control, and communication [21]. Some firms rely on formal rules and regulations and strict control, whilst other companies prefer flexibility and employees involvement in decision-making. Individual organizations tend to have their distinct management styles. Significant differences in the management styles of the alliance partners are likely to cause problems in communication and conflicts between the partners. This will bring about higher transaction risks to the organizations and alliance. To avoid such risks, the alliance tends to use complex contractual arrangements to regulate the partners' behaviors [22]. Written bespoke contracts are signed by all the partners [23] to avoid potential misinterpretations that may affect the alliance relationship [24]. Therefore, the following hypothesis was postulated:

Hypothesis 1. The contractual complexity of an alliance is affected by the differences in management style.

Organizational response is another aspect of organizational culture. It refers to the company's responses to the external enterprises and environments [25]. Different organizational members tend to have different attitudes towards external environments. Some companies prefer independent operation, while others prefer to establish close relationship with external organizations. The inconsistence of the alliance partners' responses to external environment has a direct impact on the alliance governance [15]. For example, if a company is open-minded and tends to trust others but its partners are suspicious, the mutual willingness of both parties is not likely to be achieved. Collaboration requires exchange of attitudes and information [26]. The partners tend to become distrustful when they have different tendencies in sharing information and accepting others' advices. Moreover, when the partners have different attitudes towards the common stakeholders, such inconsistence may lead to malfunction of the alliance relationship. Similarly, inconsistent responses to incidents may result in mistrust. The alliance partners may refuse to make commitment and act independently if they expect that other partners will not act as expected. The above problems that are incurred by significant differences in organizational responsiveness may require complex contractual arrangements to regulate the behaviors of each party. Therefore, the second hypothesis is set out as following:

Hypothesis 2. The contractual complexity of an alliance is affected by the differences in organizational responsiveness.

2.2. Mutual Trust and Contractual Complexity

The concept of trust has two dimensions: (1) goodwill trust and (2) competence trust [19, 20]. The mutual trust can be classified into mutual goodwill trust and mutual competence trust. Mutual goodwill trust refers to the belief of goodwill, responsible, and reliable trust between alliance partners [27]. To avoid the cooperation problems (e.g., communication and conflicts) incurred by the differences in management styles, the alliance partners tend to use complex contracts to regulate the behaviors of the participants and achieve the targets of cooperation. However, high level of mutual goodwill trust among the alliance partners may facilitate the information sharing and then effectively avoid conflicts [28]. Thus, the alliance partners with high level of mutual trust tend to reduce the reliance on complex contracts to save the contracting costs [28]. It is therefore likely that mutual goodwill trust may mitigate the distrust and conflicts resulted from organizations cultural differences.

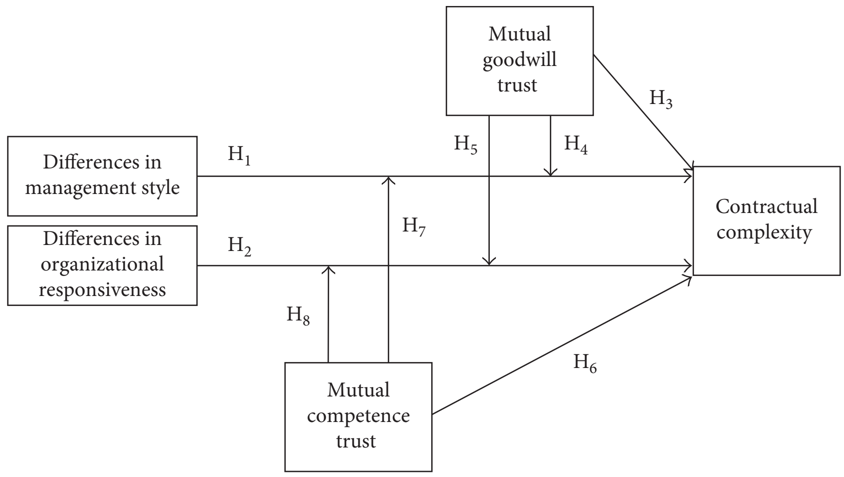

Figure 1: Conceptual model for the relationships between OCD, MT, and CC.

Hypothesis 3. The contractual complexity of an alliance is affected by mutual goodwill trust.

Hypothesis 4. The relationship between the differences in management style and the contractual complexity is moderated by mutual goodwill trust.

Hypothesis 5. The relationship between the differences in organizational responsiveness and the contractual complexity is moderated by mutual goodwill trust.

Competence trust focuses on the objective aspect of trust [20]. It relates to the belief of whether the partners will fulfill their commitments or not. For example, will the partners' activities and behaviors within the alliance be trusted? Do the partners have the claimed technologies and resources? Whether the partners will use these technologies and resources in the activities and operations of the alliance [20]? If a company believes that its partner can complete the work as expected under disadvantageous conditions, the company tends to expand the scope of cooperation, which will bring the risks of partners' opportunistic behaviors to the company [29]. Jiang [30] argued that if the companies trust their partners' competence in understanding and using new knowledge and techniques, they tend to adopt more defensive actions to reduce the risk of losses of core knowledge and techniques. However, if the companies trust their partners' competence, they are more likely to (1) accept the partners' suggestions and (2) accept the short-term losses based on their anticipation for the future performance [31]. The mutual competence trust may improve the communications between the partners and reduce the chance of conflicts. It is therefore likely that the relationship between organizations cultural differences and contractual complexity is moderated by the level of mutual competence trust.

Hypothesis 6. The contractual complexity of an alliance is affected by mutual competence trust.

Hypothesis 7. The relationship between the differences in management style and the contractual complexity is moderated by mutual competence trust.

Hypothesis 8. The relationship between the differences in organizational responsiveness and the contractual complexity is moderated by mutual competence trust.

The conceptual model based on the above hypotheses is described in Figure 1.

3. Research Methods

3.1. Measures. This study aims to explore the interrelationships between multiple variables, which indicates a correlational research study in nature. A questionnaire survey was conducted to collect the quantitative data for this study. The questionnaire was designed based on literature review, expert comments, and preliminary field study. The research variables were operationalized as follows.

3.1.1. Contractual Complexity (CC). The behaviors of alliance partners are confined by the contracts between all parties. The research on the alliance contracts can be traced back to the research by Parkhe [32], who listed out the contractual conditions, including (1) regularly report all the relevant transactions; (2) timely record notice of any departures from the agreement; (3) have the right to check and audit all the relevant records through chartered accountants; (4) some particular information or resources are restricted by Certified Public Accountants; (5) stop using proprietary information even after termination of agreement; (6) termination date; (7) arbitration clauses; and (8) lawsuit provisions. Following Reuer and Ariño [12] and Lumineau and Malhotra [13], the contractual complexity was calculated by the following formula:

$$\text{contractual complexity} = \frac{1}{36}\sum D_i, \qquad (1)$$

where D_i ($i = 0, 1, \ldots, 8$) represents that the ith clause was adopted, and zero otherwise.

3.1.2. Organizational Cultural Differences (OCD). In this study, organizational cultural differences include the differences in the partners' management styles (MD) and differences in organizational responsiveness (RD). Differences in the management style were measured by the following three scale items: (1) company/partner relies on informal organizations (e.g., with loose control and monitor) [15, 21, 33]; (2) company/partner's decision making relies on top management [15, 21, 34]; and (3) company/partner organization is open [15, 33, 34]. The organizational response differences were measured by the following 3 scale items: (1) company/partner trusts others (e.g., willing to share sensitive information) [15, 35]; (2) company/partner uses an open approach to solve conflicts [36]; and (3) company/partner is flexible [15, 37]. In the questionnaire, the scale items for measuring the differences in management styles (MD) and differences in organizational responsiveness (RD) were rated using the 5-point Likert scale. Respondents were required to rate the scale items based on their perceptions about their company's organizational culture and the alliance partner's organizational culture. The organizational cultural differences were calculated using the following formula:

$$\mathrm{OCS} = |\mathrm{OCC} - \mathrm{OCP}|, \tag{2}$$

where OCD represents the organizational cultural differences between the company and alliance partner; OCC represents the organizational culture of the company; and OCP represents the organizational culture of the alliance partner.

3.1.3. Moderator-Mutual Trust (MT). Following Zaheer et al. [38], goodwill trust and competence trust were measured using 4 scales and 3 scales, respectively. The mutual goodwill trust (MGT) includes the following: alliance partners are just in negotiation [29, 38, 39]; alliance partners are very reliable [29, 30, 38]; and alliance partners will act as expected [29, 38]. The mutual competence trust (MCT) comprises the following: alliance partners have good credit [29, 30, 39]; alliance partners have sufficient capital resources [29, 30, 39]; and alliance partners have sufficient human resources [29, 30, 39]. Following Huang et al. [18], the level of mutual goodwill trust can be calculated using the following formula:

$$\mathrm{MT} = \mathrm{TF} + \mathrm{TP} - |\mathrm{TF} - \mathrm{TP}|, \tag{3}$$

where MT represents mutual trust; TF represents trust of company; and TP represents trust of partner. The mutual trust is not only determined by the trust of both sides of alliance but also depends on the difference of trust of both sides.

3.1.4. Control Variables. Size differences (SD) may influence the stability of the alliance [40] and benefits allocation between partners [41]. Thus, SD was introduced as a control variable in this study. Size was measured by the number of employees. Prior relationship length (PRL) between the partners is likely to influence the degree of contractual details [42], and it was characterized by the duration of the prior relationship between the partners [13]. Asset specificity (AS) has a strong explanation power about the contractual governance [9, 43], and it was also introduced as a control variable. AS includes the following: the extent to which the resources are wasted after the termination of cooperation [44, 45]; the extent to which the adjustments have been made during the operation [45, 46]; and the time and capital required to train and evaluate collaborative partners [44, 47].

3.2. Sample and Data Collection. This study aims to investigate the issues regarding cooperation of project alliances; therefore, the respondents of the survey included the personnel who are familiar with the project alliance management. A screening question (i.e., are you familiar with the alliance management?) was included in the questionnaire to ensure that only the questionnaires completed by those who were familiar with alliance management were included in the subsequent data analysis. Before issuing the formal questionnaires, we conducted a pilot study in three construction firms who have experienced nonequity alliances. The questionnaires were completed by the top management personnel of the firms. Upon completion, respondents evaluated the contents of the questionnaire, understandability of questions and terminology, and proposed amendments. According to the feedback, we deleted the items that does not conform to the actual situation and amended the items that may cause confusions.

Simple random sampling methods were used to determine the sample for this study. Four hundred and eighty construction enterprises were randomly selected from the yellow pages of construction business in China and 320 construction enterprises were sourced through the research team's personal professional networks. The initial contact was made by telephone to request their participation in this research. The questionnaires were distributed to the participants by e-mail or post upon their agreement to participate in the research. A total of 580 construction enterprises agreed to participate in the survey and produced 202 valid questionnaires, thus yielding a valid response rate of 25%. There is a big gap between the numbers of companies agreed to participate and valid questionnaires received in this survey. The main reasons may include the following: (1) the questionnaires completed by those who were not familiar with alliance management were excluded; (2) incomplete questionnaires were excluded; and (3) many companies who agreed to participate in this research failed to find suitable respondents or return the questionnaires in the required timeframe. The response rate was considered acceptable compared to the normal response rate of 20–30% reported in research of similar type in the construction industry [48–50].

Table 1: Descriptive statistics and correlations.

Variables	Mean	Min.	Max.	SD	1	2	3	4	5	6	7	8
1. CC	0.26	0.03	0.78	0.22	1	—	—	—	—	—	—	—
2. MD	2.60	1.00	3.33	0.51	0.48**	1	—	—	—	—	—	—
3. RD	2.59	1.00	3.00	0.51	0.49**	0.66**	1	—	—	—	—	—
4. MGT	5.20	2.00	8.67	1.17	−0.22**	−0.09	−0.09	1	—	—	—	—
5. MCT	5.34	2.67	8.67	1.17	0.28**	0.15*	0.16*	0.41**	1	—	—	—
6. SD	1.71	0.00	4.00	0.94	0.19**	0.08	0.07	0.04	0.08	1	—	—
7. PRL	2.29	0.00	4.00	1.18	0.06	−0.01	−0.00	−0.02	−0.02	0.09	1	—
8. AS	2.54	1.00	3.33	0.53	0.39**	0.51**	0.40**	−0.10	0.10	0.16*	−0.06	1

$N = 202$. $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$.

4. Result

4.1. Test of Reliability and Validity. The data were analyzed using IBM SPSS Statistics 20 and IBM SPSS AMOS 20. Table 1 presents the descriptive statistics and the correlation coefficients between the research variables. The validity of the data collection instrument was assessed using Cronbach's alpha (>0.7) and CITC (corrected item-total correlation) (>0.5) [51, 52]. The internal factor structure of the questionnaire was assessed by unidimensionality test (KMO > 0.7) [53]. Table 2 shows that the questionnaire has strong reliability and validity (Cronbach's $\alpha > 0.7$; CITC > 0.5). Moreover, the results of KMO (>0.7) and Barlett test (significant) show that the questionnaire is suitable for factor analysis.

The questionnaire was designed based on the existing measure scales and the feedback from the pilot study. The scale items have been well recognized in prior studies and the pilot study, which indicates that the questionnaire has good contents validity. Construct validity was evaluated by assessing convergent validity and discriminant validity of constructs. Factor loadings (>0.7), individual item reliability (>0.5), composite reliability (>0.8), and average variance extracted (>0.5) tests were used to determine the convergent validity of measured construct. The square roots of the AVE of all the variables were higher than the correlation coefficients with other constructs, demonstrating the discriminant validity of constructs [54].

Table 3 shows that factor loadings, individual item reliability, CR, and AVE met the thresholds, indicating a satisfactory level of convergent validity. From Table 4, the square roots of AVE of all the variables were higher than the correlation coefficients with other constructs, demonstrating the discriminant validity of constructs.

Table 2: Reliability test.

Variable	Items	Indicator	CITC	Cronbach's alpha	KMO (Barlett test)
AS	3	AS1	0.674	0.792	0.703***
		AS2	0.575		
		AS3	0.654		
MD	3	MD1	0.748	0.864	0.735***
		MD2	0.721		
		MD3	0.762		
RD	3	RD1	0.658	0.841	0.701***
		RD2	0.673		
		RD3	0.788		
MGT	3	GT1	0.673	0.832	0.700***
		GT2	0.761		
		GT3	0.645		
MCT	3	CT1	0.689	0.851	0.723***
		CT2	0.718		
		CT3	0.760		

$^{***}P < 0.001$.

Table 3: Convergent validity.

Indicator	Loading	Reliability	AVE	CR
AS1	0.773***	0.598		
AS2	0.735***	0.540	0.570	0.800
AS3	0.757***	0.573		
MD1	0.832***	0.692		
MD2	0.790***	0.624	0.682	0.866
MD3	0.855***	0.731		
RD1	0.718***	0.516		
RD2	0.739***	0.546	0.652	0.847
RD3	0.946***	0.895		
MGT1	0.751***	0.564		
MGT2	0.911***	0.830	0.633	0.837
MGT3	0.711***	0.506		
MCT1	0.758***	0.575		
MCT2	0.801***	0.642	0.659	0.853
MCT3	0.873***	0.762		

$^{***}P < 0.001$.

4.2. Hierarchical Regression Analysis and Hypotheses Testing. Hierarchical regression analysis was used to test the hypotheses in this research. To test the effects of organizational cultural differences and mutual trust on contractual complexity and whether the relationship between organizational cultural differences and contractual complexity is moderated by mutual trust, three regression models were examined. The first model regressed CC on the control variables, namely, AS, PRL, and SD (Model 1 in Table 5). The second model was developed by adding MD, RD, MGT, and MCT to the regression analysis (Model 2 in Table 5). The last model (Model 3 in Table 5) was built by including the

Table 4: Discriminant validity.

Variable	AS	MD	RD	MGT	MCT
AS	0.570[a]	—	—	—	—
	0.723[b]	—	—	—	—
MD	0.599[c]	0.682	—	—	—
		0.826	—	—	—
RD	0.426	0.640	0.652	—	—
	—	—	0.808	—	—
MGT	−0.072	−0.095	−0.114	0.633	—
	—	—	—	0.796	—
MCT	0.108	0.193	0.143	0.464	0.659
	—	—	—	—	0.812

[a]Diagonal for variable AVE; [b]square root AVE; [c]diagonal external variable correlation coefficient.

Table 5: Hierarchical regression analysis.

Variable	CC		
	Model 1	Model 2	Model 3
MD	—	0.172*	0.174*
RD	—	0.238***	0.233***
MGT	—	−0.305***	−0.259***
MCT	—	0.320***	0.284***
MD*MGT	—	—	−0.066
MD*MCT	—	—	0.117
RD*MGT	—	—	−0.162*
RD*MCT	—	—	0.135
AS	0.372***	0.127*	0.112
PRL	0.071	0.059	0.045
SD	0.121	0.115*	0.086
ΔR^2	0.170	0.109	0.039
R^2	0.170	0.428	0.467
F	13.445***	20.620***	15.025***

***$P < 0.001$; **$P < 0.01$; *$P < 0.05$.

product terms (e.g., MD∗MGT, MD∗MCT, RD∗MGT, and RD∗MCT) in the regression analysis.

Before conducting the hierarchical regression analysis, the issues of multicollinearity and heteroscedasticity were tested. Results (VIF < 10 (3); DW close to 2 (1.6) [55]) show that there were no significant multicollinearity and heteroscedasticity issues. SPSS 20 was used to conduct hierarchical regression analysis. Variables were centered before testing the moderated effects [56]. The results of regression analysis are presented in Table 5.

The regression analysis of Model 4 (Table 5) shows that contractual complexity is positively related to the differences of management styles ($r = 0.174$), differences of organizational responsiveness ($r = 0.233$), and mutual competence trust ($r = 0.284$), whilst it is negatively related to mutual goodwill trust ($r = -0.259$). The result provides evidence to support hypotheses 1 (i.e., CC is affected by MD), 2 (i.e., CC is affected by RD), 3 (i.e., CC is affected by MGT), and 6 (i.e., CC is affected by MCT).

The moderated effects of mutual trust on contractual complexity are analyzed by examining model 3 and model 4 (Table 5). The results show that R^2 of Model 4 was raised to 0.467 compared to that of Model 3, which indicates that Model 4 has a stronger explanation power than Model 3. Table 5 shows that the effects of the RD and MGT interaction term ($r = -0.162$) on CC are significant ($P < 0.05$), which indicates that the relationship between RD and CC was moderated by MGT. The relationship between MD and CC was not significantly ($r = -0.066$, $P > 0.05$) moderated by the MGT. The relationship between MD and CC was not significantly ($r = 0.117$, $P > 0.05$) moderated by the MCT. The relationship between RD and CC was not significantly ($r = 0.135$, $P > 0.05$) moderated by the MCT. These results provide empirical evidence to support hypotheses 5. However, hypotheses 4, 7, and 8 were not supported. The implications of the hypotheses testing results are discussed in the following section.

5. Discussion

The results of hypotheses testing show that contractual complexity is influenced by the differences in management style and organizational responsiveness. For the nonequity project alliance in the construction industry, similar organizational culture between the partners will facilitate the understanding, communication, and information sharing between them; therefore, alliance targets can be achieved without more complex contracts. On the other hand, more significant difference in management style and organizational response may lead to more difficulties in communications and higher possibility of conflicts between partners. The results support the existing research findings that the culture match and the success of alliances are positively correlated [3, 57] and that organizational cultural difference was viewed as one of the important factors influencing the project alliance contractual complexity. It establishes the relationship between the organizations' cultural difference and contractual complexity in the construction industry and expands the research on the relationship between organizational cultural difference and relational mechanisms [15]. As culture is difficult to change for all the alliance partners, they can only use complex alliance contracts to balance the relationships between all parties and minimize the risks of collaborations from organizations' cultural difference.

The results also show that contractual complexity is impacted by mutual goodwill trust and mutual competence trust. The complexity of contracts may be reduced with the increasing level of goodwill trust. Therefore, the value of goodwill trust should be emphasized no matter whether there are cultural differences between partners. Chinese people are more willing to partner with those who have "Guanxi" with them because there is a higher level of goodwill trust between them. The findings support the suggestion of Peter et al. [24] to establish goodwill trust between partners in the negotiation stage.

Mutual competence trust was found to have positive impact on contractual complexity of project alliances. The finding suggests that a higher level of mutual competence trust may result in more complex contracts. The following two possible reasons may explain why higher level of mutual competence trust tends to be associated with more complex contracts. First, higher level of mutual competence trust between partner means that they may have stronger capacity to implement the contracts; therefore, the anticipated partnership targets are likely to be achieved by setting out many aspects in the contracts without worrying about the partners' capacity to implement the contracts. Second, as suggested by [30], the partners with similar levels of competence are more likely to worry about the issue of knowledge stealing, which requires more constraints be specified in the contracts. Both aspects may lead to a higher level of contractual complexity.

The results of hierarchical regression analyses indicated that the relationship between differences in organizational responsiveness and contractual complexity was moderated by mutual goodwill trust. When there is a higher level of mutual goodwill trust between partners before entering the partnership, the partners may have good communications and less conflicts based on trust, goodwill, and kindness even if they have significant differences in organizational responsiveness, which involves the firm's attitudes toward external partners and the level of trust [15].

6. Conclusions

This study investigated the impact of organizations cultural difference on project alliance contractual complexity and the moderated role of mutual trust. Through the empirical analysis of a sample of 202 project alliances in the construction industry, the study found that the project alliance contractual complexity was influenced by differences in management style, differences in organizations response, mutual goodwill trust, and mutual competence trust. The relationship between differences in organizations' response and project alliance contractual complexity was moderated by the mutual goodwill trust.

The findings may have some important practical implications. For the nonequity project alliances in the construction industry, organizations' cultural difference has a significant impact on the selection of partners and project alliance governance. Due to the area characteristics of the construction industry, it is more difficult to adjust the organizational culture based on a certain rule. When the partners have more differences in their organizational cultures, they have to adopt complex alliance contracts, leading to more costs of implementing a contract. Therefore, when the firms seek to form project alliance, the management should consider the organizational cultural differences among the partners. The firms with more significant differences in organizational cultures may not be appropriate to be selected as the alliance partners. If they have selected the partners, the firms need to recognize the level of organizational cultural differences and then determine the proper contractual complexity of the project alliance.

Furthermore, the direct effect and moderator role of the mutual goodwill trust needs to be considered in the context of Chinese construction project. The existence of "Guanxi" implies that the mutual goodwill trust plays an important role in the Chinese business environments. Higher level of mutual goodwill trust among alliance partners may reduce the impact of organizations' response difference on contractual complexity, thus reducing the alliance contractual costs. The establishment of mutual goodwill trust between alliance partners will not only reduce the costs of making contracts but also the costs of implementing the contracts.

While the results of this research help to understand the effect of organizational cultural differences and mutual trust on contract management of nonequity construction project alliances, several limitations are noteworthy. First, the generalizability of the findings may need to be calibrated considering the context of China-based data collection in this research. The data were collected from nonequity project alliances in the construction industry in China. Therefore, the conclusions of this study may have difficulties to be generalized to other population (e.g., equity alliances, other industries, and other countries). It is suggested that, in future studies, the research methods and procedures of this study could be repeated in other contextual backgrounds such as different countries and industries and to test the framework of this research to reach a more generalizable conclusion. Next, the organizational culture, contractual complexity, and mutual trust that we have observed represent the status of a particular time. However, these variables may have changes with time. In a future study, the dynamic changing process of the variables may be investigated.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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