Case Study

Prioritizing Construction Risks Using Fuzzy AHP in Brazilian Public Enterprises

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Abstract: Risks capable of impacting project objectives are intrinsic to the construction industry. Effective risk analysis has key importance to professionals concerned with construction goals, especially in public enterprises, given the amount of money invested and the demand for modern infrastructure. Therefore, this study aims to identify the main public construction risks and present a practical fuzzy analytic hierarchy process (AHP) model to prioritize these risks in Brazilian public enterprises. The model is divided into three steps: (1) risk identification and development of the risk breakdown structure, (2) pairwise comparisons, and (3) risk prioritization. Throughout the case study, 54 risks were identified, which were organized into eight categories. The major risk in the Brazilian scenario was "difficulty in environmental licensing." Although this study focused on a specific context, its methodology provides a reliable and practical framework that can be adjusted to various construction projects worldwide to assess risks. Additionally, the identified risks can provide sound guidance to practitioners globally, because their elicitation was based on studies concerning different countries. **DOI: 10.1061/(ASCE)CO.1943-7862.0001606.**

Introduction

Regardless of country or city, construction ventures are known for their uniqueness (Zou et al. 2010; Pawan and Lorterapong 2016), their complexity and technological demands (Li et al. 2013a; Pawan and Lorterapong 2016), involving the interests of numerous stakeholders (Khazaeni et al. 2012), and large amounts of investment (Li and Zou 2011). These characteristics bring uncertainty into projects (Abdelgawad and Fayek 2010; Pawan and Lorterapong 2016); therefore, the occurrence of risks capable of affecting the objectives planned for projects is inherent to the construction industry (Nieto-Morote and Ruz-Vila 2011; Khazaeni et al. 2012; Taylan et al. 2014; Xia et al. 2017). Risk can be defined as an uncertain event with positive or negative impacts on project goals, if it occurs (ISO 2009; Cretu et al. 2011; Nieto-Morote and Ruz-Vila 2011; PMI 2013).

Public construction projects, especially so-called megaprojects, frequently fail to achieve their goals due a lack of effective risk management (Cretu et al. 2011). In Europe and North America, studies concerning public enterprises have revealed cost overruns in 86% of the 258 projects examined (Flyvbjerg et al. 2007). According to the authors, the primary cause for this is related to poor risk management during cost estimation. In such contexts, risk analysis has been acknowledged as essential for construction projects in order to improve overall performance and achievement of goals (Zeng et al. 2007; Nieto-Morote and Ruz-Vila 2011; Jato-Espino et al. 2014; Rahimi et al. 2018).

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Effective and consistent risk analysis by traditional techniques and methods (e.g., fault tree analysis, Monte Carlo analysis, probabilistic analysis) requires reliable and qualified input data, which are difficult to gather or, in some cases, unavailable in the construction industry (Zeng et al. 2007). As a consequence, the uncertainties related to this industry are not a simple matter to tackle (Jato-Espino et al. 2014).

To overcome this matter, new techniques and methods have been proposed in the literature. In particular, the fuzzy analytic hierarchy process (FAHP)—a method that combines fuzzy set theory (FST) and the analytic hierarchy process (AHP)—has a growing number of successful applications in construction projects. For instance, Zhang and Zou (2007) applied a FAHP to propose a risk assessment approach to effectively evaluate the level of risk in Chinese joint-venture construction projects. Abdelgawad and Fayek (2010) used a FAHP to overcome the limitations of the failure mode and effect analysis (FMEA), using FST concepts to outline the interconnection between impact, probability of occurrence, detection/control, and level of criticality of risk events. Li and Zou (2011) developed a FAHP model to analyze the risks involved in public–private partnership (PPP) concession projects. The authors compared the results obtained by their model with a straight AHP, concluding that FAHP can improve the precision of risk assessment and reduce experts' subjectivity. Elbarkouky et al. (2016) presented a novel fuzzy arithmetic approach based on FST and AHP concepts to determine construction project contingencies.

The FAHP is a structured method recommended for situations in which input data are vague or limited; using this method, risk analysis can be carried out through subjective concepts defined, mathematically, by FST (Kahraman 2008; Nieto-Morote and Ruz-Vila 2011; Elbarkouky et al. 2016). Furthermore, the FAHP is suitable for handling uncertainties and inaccuracies inherent to the risk analysis process (Zeng et al. 2007), especially in complex construction projects, in which there are many unknown risk sources (Khazaeni et al. 2012) and decision making requires subjective judgment established on robust logical reasoning (Zhang and Zou 2007).

Despite the increasing number of publications concerning the FAHP for risk assessment in the construction industry, this paper's

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authors identified three main issues in previous studies for practical applications:

- Nonconsideration of risk as the product of its probability of occurrence and its impact on project goals (Zhang and Zou 2007; Zayed et al. 2008; Li and Zou 2011; Yang and Wei 2011; Li et al. 2013b);
- Omission of consistency analysis of FAHP matrices (Zeng et al. 2007; Khazaeni et al. 2012; Li et al. 2013b; Taylan et al. 2014; Silva et al. 2015; Elbarkouky et al. 2016);
- Complexity of mathematical formulations (Zeng et al. 2007; Nieto-Morote and Ruz-Vila 2011; Li et al. 2013b; Elbarkouky et al. 2016), which may make the FAHP too mystifying for it to be widely adopted in practice.

However, recent studies related to new risk analysis techniques have not solely been based on the FAHP. The single approach of the analytic hierarchy process has been proposed by many studies as a multicriteria decision-making method in construction (Jato-Epsino et al. 2014) for areas such as risk assessment. For example, Zayed et al. (2008) designed a risk index to evaluate the effect of sources of risk and uncertainty inherent to highway projects using the AHP to assess the weights of risk areas and subareas. In order to improve the consistency of the comparison matrices in the AHP, Li et al. (2013a) presented an improved AHP for risk identification. Despite the AHP's ease of use and flexibility of application, FAHP needs to be considered when the level of uncertainty is not low in establishing crisp numbers (Lee 2015), since the FAHP is a robust mathematical method developed to manage uncertainties in subjective judgments. To tackle problems in which there are meaningful interrelationships among elements within the same cluster, the analytic network process (ANP) is a method frequently used in construction risk assessment (Lu et al. 2007; Chen et al. 2011; Boateng et al. 2015; Liu et al. 2016). Nonetheless, it is not only more stiff, but also more time consuming than both the AHP (Jato-Espino et al. 2014) and the FAHP; as a result, its use by practitioners may be prevented. Another technique that has been presenting successful applications in construction risk analysis is the artificial neural network (ANN) (Jin and Zhang 2011) and ANNs combined with fuzzy set theory (Jin 2011; Ebrat and Ghodsi 2014). Although ANNs can aid in assessing risks satisfactorily, they requires plenty of data, because machine learning is used to infer weights that best suit a particular database. In addition, the neural network construction process by both ANNs and fuzzy ANNs has some drawbacks when compared to the FAHP: (a) it can be more time consuming, because it may require some trial and error; (b) it is less transparent, and thus harder to comprehend; and (c) it allows a smaller extent of control over the final status of network weights.

The objectives of this research are (1) to identify the main public construction risks and categorize them into a risk breakdown structure (RBS) concerning Brazilian public enterprises, and (2) to present a practical FAHP model to prioritize these risks, addressing the three issues verified in previous studies. Although this study was conducted based on a Brazilian scenario, its methodology presents a detailed framework for risk assessment that can be easily adapted for other construction projects worldwide when there is no available data to support traditional methods. Moreover, the results can provide guidance for risk identification in public enterprises, because risks were elicited through literature related to different contexts. Therefore, it is believed that this research presents meaningful resources for risk management with broad implications in the construction industry.

Background

This section provides necessary background related to the FST and AHP concepts applied in this paper.

Background on Essential FST Concepts Applied in the FAHP

FST was introduced by Zadeh (1965) to mathematically deal with complex problems and their uncertainty and imprecision using subjective assessments. Fuzzy logic combined with possibility theory enables analysis by linguistic variables instead of numerical data gathered through long observations (Abdelgawad and Fayek 2010). Subsequently, FST concepts necessary to the development of this research are explained in accordance with Klir and Yuan (1995).

A fuzzy set A within the universal set of discourse X is defined by a membership function $\mu_A(x)$, which assigns to each element x a membership grade that represents the level of compatibility or similarity of x with the concept illustrated by the fuzzy set. Hence, a range of values can be assigned to elements in order to express the degree to which they fit the set; the most common range of $\mu_A(x)$ to map each element x in X is the real interval [0, 1]. This capacity to indicate a membership grade within a specified interval rather than a value of either 1 or 0 as in classical (crisp) sets is essential to incorporating vagueness and handling uncertainties (Buckley 1985).

The utility of FST particularly relies on its ability to construct appropriate membership functions to adequately capture the concepts and the meanings of linguistic variables used in applications (Klir and Yuan 1995). Membership functions with triangular shapes have been successfully employed in construction risk analysis (Nieto-Morote and Ruz-Vila 2011; Khazaeni et al. 2012; Lee 2015). Furthermore, triangular membership functions accurately handle the imprecision of assessments by linguistic variables in FST modeling (Pedrycz 1994). According to the author, a triangular fuzzy number can be denoted as $\tilde{t} = (l, m, u)$, where $l < m < u$; the membership function $\mu_{\tilde{t}}(x)$ of $\tilde{t}$ is a triangle with base within the interval $[l, u]$ and vertex in $x = m$. Thus, it can be described as

$$\mu_{\tilde{t}}(x) = \begin{cases} \dfrac{x-l}{m-l} & l \le x < m \\ 1 & x = m \\ \dfrac{u-x}{u-m} & m < x \le u \\ 0 & \text{other cases} \end{cases} \tag{1}$$

Another main concept of the FST is the α-cut; the α-cut of a fuzzy set A is the crisp set A^α that comprehends all elements of the universal set of discourse X whose membership grades in A are greater than or equal to the value assigned to α. The α-cut intervals of $\tilde{t}$ are then defined by Eq. (2):

$$A^\alpha = [l + (m-l).\alpha, u - (u-m).\alpha] \tag{2}$$

According to the extension principle (Zadeh 1965), the arithmetic laws among two triangular fuzzy numbers ($\tilde{t}_1$ and $\tilde{t}_2$) are as follows:

Fuzzy addition:

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{3}$$

Fuzzy multiplication:

$$(l_1, m_1, u_1) \otimes (l_2, m_2, u_2) \approx (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \quad (4)$$

Fuzzy multiplication by a scalar:

$$(\lambda, \lambda, \lambda) \otimes (l_1, m_1, u_1) = (l_1 \times \lambda, m_1 \times \lambda, u_1 \times \lambda), \ \ \lambda > 0, \lambda \epsilon R \quad (5)$$

Fuzzy inverse:

$$(l_1, m_1, u_1)^{-1} \approx \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \quad (6)$$

Background on Essential AHP Concepts Applied in the FAHP

The AHP was proposed by Saaty (1980) to derive dominance priorities from pairwise comparisons between alternatives, concerning common criteria or attributes (Saaty 1994). Pairwise comparisons collected from expert judgments enable, in a natural way, the handling of situations that are difficult to effectively quantify (Saaty 1980). Another advantage of the AHP is that it can be associated with different methods, such as linear programming, quality function deployment, FST, and so forth (Kuo and Lu 2013; Jato-Espino et al. 2014).

Saaty (1980) divided the AHP into 11 main steps. Nonetheless, the application of the AHP can be carried out in two general phases, hierarchy design and evaluation (Lee 2015). During the hierarchy design phase, the first step is to identify all relevant elements with respect to the problem. In the risk management context, a common type of hierarchy is the RBS (Carr and Tah 2001; PMI 2013), which is frequently developed using the brainstorming technique (Saaty 1980; ISO 2009; PMI 2013).

The second phase—evaluation—is concerned with pairwise comparisons between alternatives carried out based on the fundamental scale of Saaty (1990) and the resulting prioritization (Lee 2015). Pairwise comparisons (E_i, E_j) can be expressed by the $n \times n$ $[\boldsymbol{E}]$ matrix, which is known as the reciprocal comparison matrix. The principal eigenvector of $[\boldsymbol{E}]$, when normalized, provides the priority vector of the elements e_{ij} (Saaty 1980). The consistency of a judgment can be examined by the principal eigenvalue $\lambda_{\max}$ of the reciprocal comparison matrix (Saaty 1980).

Research Methodology

The methodology to first identify construction risks and then prioritize these risks with regard to Brazilian public enterprises was divided into three steps: (1) risk identification and development of the RBS, (2) pairwise comparisons, and (3) risk prioritization. Fig. 1 presents the framework proposed by this study for assessing construction risks semiquantitatively. It not only shows all steps and the required techniques for prioritizing risks, but also comprises all the contributions that each step provides to the risk management body of knowledge.

Step 1: Risk Identification and RBS Development

It was verified that most studies concerning construction risks identify risk events in the scientific literature (Zayed et al. 2008; Kuo and Lu 2013; Liu et al. 2016). Indeed, risk identification

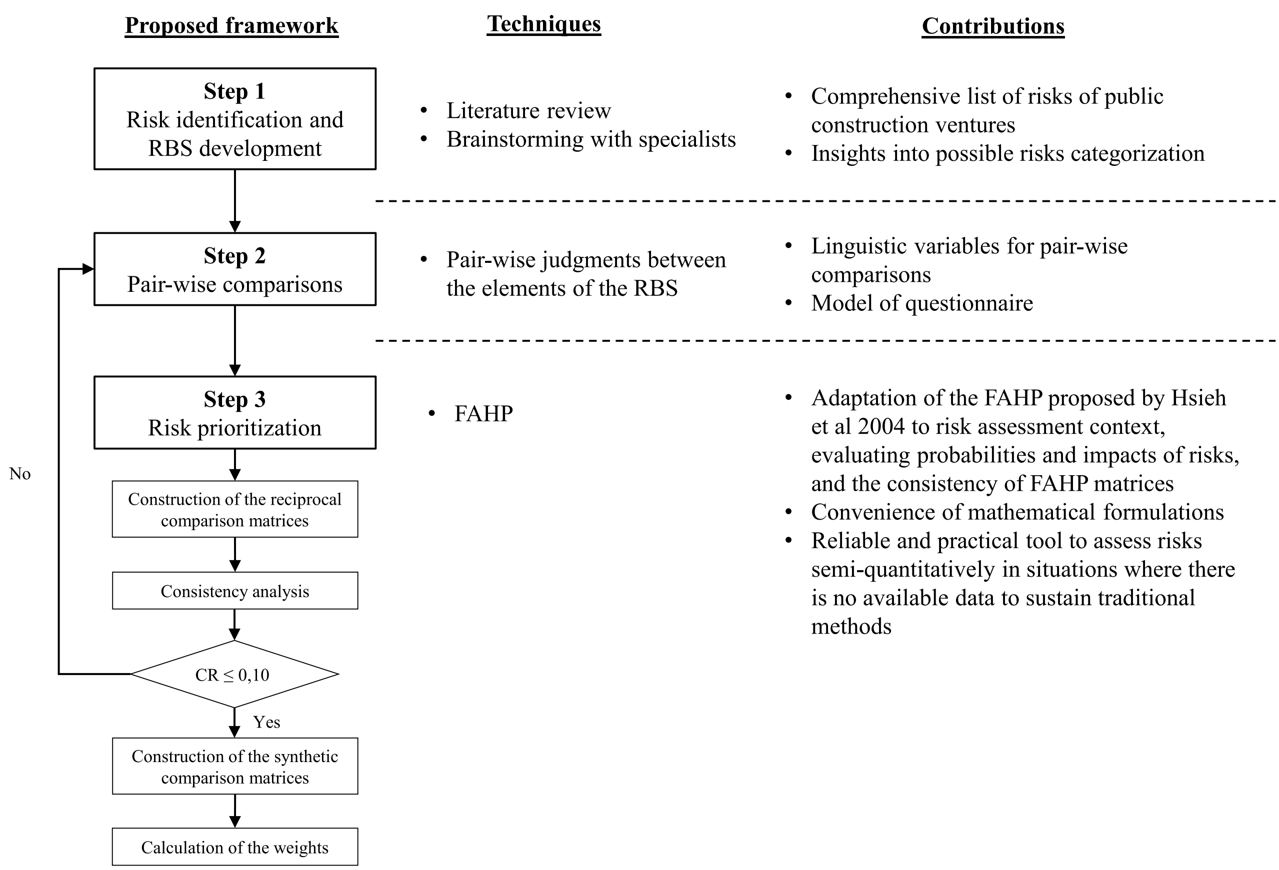


Fig. 1. Framework for risk prioritization by the proposed FAHP and its techniques and contributions.

Table 1. Profiles of subject matter experts

Panelist	Sector	Experience (years)	
		Construction	Risk management
Panelist A	Public	10	5
Panelist B	Public	12	3
Expert 1	Public	20	—
Expert 2	Public	15	15
Expert 3	Public	10	6
Expert 4	Private	17	10
Expert 5	Private	18	8
Expert 6	Public	7	4
Expert 7	Private	25	20

Note: Public = state-owned companies, federal autarchies, and controlling and supervisory agencies; and Private = insurance companies, contractors, construction risk management companies, and independent consultants.

through the literature is endorsed as the most used instrument by Azevedo et al. (2014), who carried out a review of risk management in construction. Therefore, risks in Brazilian public enterprises were identified and elicited from the literature.

The RBS was then developed using the brainstorming technique procedures suggested by the Annex B of ISO (2009). Small group sessions, referred to as advanced risk-elicitation interviews, have proven to be the most productive procedure for the elicitation of risks (Cretu et al. 2011). Therefore, two subject matter experts (SME) in construction risks were chosen from different public agencies as brainstorming panelists (Table 1) to give their opinions on the identified risks and establish their RBS with respect to the Brazilian context.

During the RBS development, risks were grouped according the relation category–risk. The ability of panelists to categorize risks according to their nature is a key factor in the effectiveness and validity of the FAHP (Zhang and Zou 2007). Two boundary conditions had to be satisfied: (1) hierarchy structures require elements that are mutually independent in each level, but comparable (Saaty 1990, 1994); and (2) the maximum number of elements in each level of the RBS must be within the range 7 ± 2, according to Miller's magical number (Saaty 1990; Li et al. 2013a; Lee 2015).

Step 2: Pairwise Comparisons

Comparison questionnaires were answered through pairwise judgments between elements of the RBS developed in Step 1; that is, preference relations were assigned to each pair of elements, indicating the degree of priority of one element over the other.

Due to the high uncertainty and lack of input data that construction projects may have, risk assessment based on crisp numbers is a difficult and inaccurate task to tackle, even if the best experts participate in the assessment (Abdelgawad and Fayek 2010; Nieto-Morote and Ruz-Vila 2011; Khazaeni et al. 2012). Therefore, the judgments were based only on linguistic variables, making it more convenient for the experts to compare the elements.

Table 2 presents the linguistic variables developed so that pairwise comparisons could be performed in natural language. Three linguistic variables v ("importance," "probability," and "impact") were established within the construction risk assessment context. Categories were compared with each other based on their relative importance, whereas risks were compared within a certain category in terms of their probability of occurrence and impact upon project objectives if they were to occur. Linguistic variables were characterized by five linguistic terms L ("equal," "moderate," "strong," very strong," and "extreme"). A synthetic rule g was assigned to the variable to standardize the comparisons, such as: Element X has L v compared to Element Y. A semantic rule m was established for the linguistic variables using a scale of conversion from linguistic terms to triangular fuzzy numbers (Table 3). The conversion criteria presented in Table 3 has been verified in many studies addressing risk analysis by the FAHP (Khazaeni et al. 2012; Taylan et al. 2014; Lee 2015).

Table 2. Linguistic variables—symbols and representation

Term	Symbol	Representation
Variable name	v	Importance, probability, impact
Linguistic term	L	Equal, moderate, strong, very strong, extreme
Universe of discourse	U	[1, 9]
Synthetic rule	g	Element X has L v compared to Element Y
Semantic rule	m	Scale of conversion (Table 3)

Table 3. Scale of conversion from linguistic term to $\tilde{t}$

Linguistic term	Symbol	$\tilde{t}$	$\tilde{t}^{-1}$
Equal	EQ	$(1, 1, 3)$	$\left(\frac{1}{3}, 1, 1\right)$
Moderate	MO	$(1, 3, 5)$	$\left(\frac{1}{5}, \frac{1}{3}, 1\right)$
Strong	ST	$(3, 5, 7)$	$\left(\frac{1}{7}, \frac{1}{5}, \frac{1}{3}\right)$
Very strong	VS	$(5, 7, 9)$	$\left(\frac{1}{9}, \frac{1}{7}, \frac{1}{5}\right)$
Extreme	EX	$(7, 9, 9)$	$\left(\frac{1}{9}, \frac{1}{9}, \frac{1}{7}\right)$

Source: Adapted from Hsieh et al. (2004).

Note: The five triangular fuzzy numbers $\tilde{t}$ were originally proposed by Mon et al. (1994).

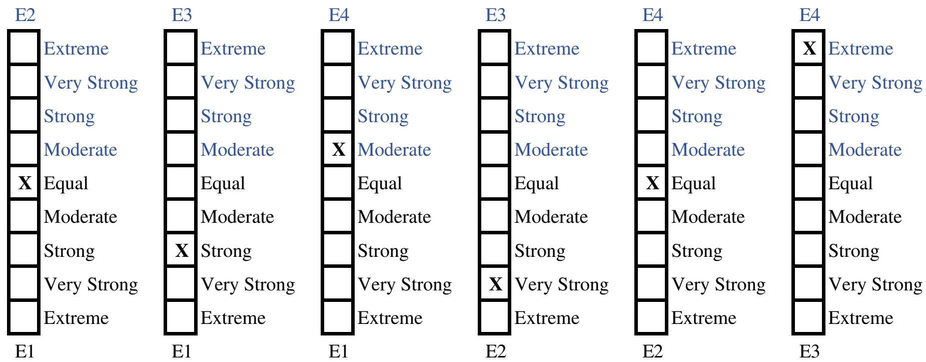
Fig. 2 presents a model of a questionnaire that can be used to perform the pairwise comparisons required by the FAHP. In addition, it illustrates judgments between four random elements using the linguistic variables described in Table 2. Such questionnaires can be easily developed using spreadsheets.

To carry out the pairwise comparisons required by the FAHP, 19 experienced practitioners were chosen from both the private and public sectors in Brazil. It is believed that a heterogeneous SME group can add different points of view to the assessment, providing not only a broader picture but also more accurate and reliable results. Seven out of 19 experts effectively engaged in this case study; that is, the response rate was approximately 35%, which was acceptable compared with the standard of 20%–30% in most questionnaire surveys in the construction industry (Hwang et al. 2015; Liu et al. 2016). The profiles of each SME group member are also presented in Table 1.

Step 3: Risk Prioritization

The objective of this step was to develop the list of risks prioritization (LRP) for the Brazilian public enterprises scenario. For this purpose, questionnaire replies from the SME group were used as input to the FAHP to estimate the priority of each risk from vague information by the FAHP. The following procedures are based on the studies of Buckley (1985), Saaty (1980), and Hsieh et al. (2004). This step was divided into four substeps, which are explained subsequently.

Through pair-wise comparisons, please judge the relative **IMPORTANCE** between the elements E1, E2, E3 and E4:



Pair-wise comparison	Judgments according to the illustrative questionnaire
E1-E2	*E1* has *equal importance* comparing to *E2*
E1-E3	*E1* has *strong importance* comparing to *E3*
E1-E4	*E4* has *moderate importance* comparing to *E1*
E2-E3	*E2* has *very strong importance* comparing to *E3*
E2-E4	*E2* has *equal importance* comparing to *E4*
E3-E4	*E4* has *extreme importance* comparing to *E3*

Fig. 2. Model questionnaire.

Substep 1: Construction of the Reciprocal Comparison Matrices

The first substep consisted of assigning a reciprocal comparison matrix to each questionnaire by converting linguistic variables into triangular fuzzy numbers $\tilde{t} = (l, m, u)$ through Table 3. The universe of discourse for $\tilde{t}$ is defined in [1, 9]; the membership function $\mu_T(x)$ assigns to each $x \in U$ a real number within the interval [0, 1]; the α-cuts were calculated by Eq. (2). Then, reciprocal comparison matrices $[\tilde{\boldsymbol{T}}]$ were formulated as follows:

$$[\tilde{\boldsymbol{T}}] = (\tilde{\boldsymbol{t}}_{\boldsymbol{ij}})_{\boldsymbol{n}\times\boldsymbol{n}} = \begin{bmatrix} (\mathbf{1},\mathbf{1},\mathbf{1}) & \ldots & (\boldsymbol{l}_{\mathbf{1}\boldsymbol{n}},\boldsymbol{m}_{\mathbf{1}\boldsymbol{n}},\boldsymbol{u}_{\mathbf{1}\boldsymbol{n}}) \\ \vdots & \ddots & \vdots \\ (\boldsymbol{l}_{\boldsymbol{n}\mathbf{1}},\boldsymbol{m}_{\boldsymbol{n}\mathbf{1}},\boldsymbol{u}_{\boldsymbol{n}\mathbf{1}}) & \ldots & (\mathbf{1},\mathbf{1},\mathbf{1}) \end{bmatrix} \tag{7}$$

where $\tilde{t}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ e $\tilde{t}_{ij}{}^{-1} = \left(\frac{1}{u_{ji}} \frac{1}{m_{ji}} \frac{1}{l_{ji}}\right)$, $\forall\ i, j \in \{1, \ldots, n\}$ e $i \neq j$; $\tilde{t}_{ij} = (1, 1, 1)$, $\forall\ i = j$; and $\tilde{t}_{ij}$ represents the importance that element E_i has in comparison to element E_j according to a certain expert.

Substep 2: Consistency Analysis

The consistency of reciprocal comparison matrices is an important issue to be assessed because of its potential impacts on the analysis results (Xu and Wang 2013). In this research, Saaty's consistency test (Saaty 1980) was used because of its wide application in the AHP and FAHP (Boateng et al. 2015). Moreover, it defines a threshold for judgment inconsistencies, within which it is possible to work.

Saaty's consistency test deals only with crisp numbers; thus, it was necessary to convert the fuzzy numbers of all $[\tilde{\boldsymbol{T}}]$ into crisp numbers. It has been proven that if a reciprocal matrix made up of crisp numbers is consistent, the corresponding matrix made up of fuzzy numbers is also consistent (Buckley 1985). The conversion was tackled using the α-cut technique, assuming $\alpha = 1$, which constrains x to the interval in which all elements are totally compatible with the fuzzy set T.

A given positive reciprocal matrix is consistent if and only if $\lambda_{\max} = n$ (Saaty 1980), where $\lambda_{\max}$ is the principal eigenvalue and n is the number of elements of the matrix $[\boldsymbol{E}]$ made up of crisp numbers. It is observed that $\lambda_{\max} \geq n$ is always true. Moreover, a consistency index (CI) can be estimated by Eq. (8). The closer $\lambda_{\max}$ is to n, the smaller the deviation index is, and thus the result becomes more consistent

$$\mathrm{CI} = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{8}$$

Saaty's consistency test results in the calculation of the consistency ratio (CR), as follows

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{9}$$

where RI is the random index (Saaty 1980).

If the CR ≤ 0.10, the matrix is assumed to be consistent (Saaty 1980). The process recommended by Saaty and Tran (2007) was used for matrices that presented CR > 0.10, and, through it, experts were asked to reconsider their most inconsistent judgments. It is important to emphasize that this process did not try to force consistency; it only offered an opportunity to reassess pairwise comparisons.

Substep 3: Construction of the Synthetic Comparison Matrices

Since the judgments of each expert resulted in a different matrix $[\tilde{\boldsymbol{T}}]$, it was necessary to integrate the opinion of different experts to form one synthetic comparison matrix. Therefore, the elements of the synthetic comparison matrices were calculated using the geometric mean (Buckley 1985), as in Eq. (10):

$$\tilde{t}_{ij} = (\tilde{t}_{ij}^{1} \otimes \tilde{t}_{ij}^{2} \otimes \ldots \otimes \tilde{t}_{ij}^{E})^{1/E} \tag{10}$$

where superscript E = total number of experts.

If $[\tilde{\boldsymbol{T}}]$ is consistent, its synthetic comparison matrix will also be consistent (Buckley 1985).

Substep 4: Calculation of the Weights

First, for each synthetic comparison matrix calculated through Substep 3, the fuzzy geometric mean $\tilde{r}_i$ and the fuzzy weight $\tilde{w}_i$ of each element was defined using Eqs. (11) and (12) (Buckley 1985)

$$\tilde{r}_i = (\tilde{t}_{ii} \otimes \tilde{t}_{ij} \otimes \ldots \otimes \tilde{t}_{in})^{1/n} \tag{11}$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_i \oplus \ldots \oplus \tilde{r}_n)^{-1} \tag{12}$$

where $\tilde{t}_{in}$ is defined as the pairwise comparison of element i with element $j, \forall\ i, j \in \{1, \ldots, n\}$; $\tilde{r}_i$ and $\tilde{w}_i$ are the fuzzy geometric mean and the fuzzy weight of element i, respectively; and n = number of elements of the matrix.

Because elements can refer not only to categories but also to risks, it was necessary to distinguish the symbols $\tilde{r}_i$ and $\tilde{w}_i$ in the following ways:

- $\tilde{r}_k^C$ and $\tilde{w}_k^C$—fuzzy geometric mean and fuzzy weight, respectively, of category k of risk;
- $\tilde{r}_i^P$ and $\tilde{w}_i^P$—fuzzy geometric mean and fuzzy weight, respectively, of the probability of risk i; and
- $\tilde{r}_i^I$ and $\tilde{w}_i^I$—fuzzy geometric mean and fuzzy weight, respectively, of the impact of risk i.

Risk is defined primarily as the product of its probability of occurrence and its impact on project goals (Zeng et al. 2007; ISO 2009; Cretu et al. 2011; Nieto-Morote and Ruz-Vila 2011; PMI 2013; Kuo and Lu 2013; Liu et al. 2016; Elbarkouky et al. 2016). Hence, the FAHP proposed by Hsieh et al. (2004) for assessing the selection of building planning and design alternatives was adapted to the risk analysis context. In consequence, the fuzzy weight $\tilde{w}_i^R$ of each risk i was calculated by the multiplication of $\tilde{w}_i^P$ and $\tilde{w}_i^I$, weighted by the fuzzy weight $\tilde{w}_k^C$ concerning the category k of the risk analyzed, as follows:

$$\tilde{w}_i^R = \tilde{w}_k^C \otimes (\tilde{w}_i^P \otimes \tilde{w}_i^I) \tag{13}$$

Since the fuzzy weights $\tilde{w}_i^R$ defined by Eq. (13) are triangular fuzzy numbers represented by triplets $(L_{\tilde{w}_i^R}, M_{\tilde{w}_i^R}, U_{\tilde{w}_i^R})$, it was necessary to defuzzify them in order to develop a nonfuzzy risk ranking. This procedure consisted of determining the best nonfuzzy performance value for each $\tilde{w}_i^R$ (Hsieh et al. 2004). Methods of defuzzification usually consist of the mean of maximal (MOM) method, the α-cut technique, and the center of area (COA) method (Hsieh et al. 2004; Kuo and Lu 2013). The COA method was used in this research due its simplicity and practicality; moreover, it does not require the preferences of experts to be brought in (Hsieh et al. 2004). The COA of the fuzzy weight $\tilde{w}_i^R$ of each risk i can be defined as follows:

$$w_i^R = \frac{[(U_{\tilde{w}_i^R} - L_{\tilde{w}_i^R}) + (M_{\tilde{w}_i^R} - L_{\tilde{w}_i^R})]}{3} + L_{\tilde{w}_i^R} \tag{14}$$

where w_i^R is the nonfuzzy weight.

Finally, for each risk $i, \forall\ i \in \{1, \ldots, n\}$, the normalized nonfuzzy weight W_i was calculated, aiming to establish a percentage risk ranking, that is, the list of risks prioritization.

$$W_i = \frac{w_i^R}{\sum_{i=1}^{n} w_i^R} \times 100\% \tag{15}$$

where n = total number of risks.

Results and Discussion

The RBS (Fig. 3) built for a Brazilian public construction scenario comprehends 54 risks identified in the literature, which were categorized into eight categories. The prioritization of these risks is shown in the LRP (Table 4).

If the Pareto principle—also known as the 80/20 rule—is applied to the developed LRP, the top 11 risks (20% of the total of 54 risks) should be responsible for 80% of the problems and difficulties in Brazilian public enterprises. For further analysis, these risks were called Group $R_{20\%}$ (GR20%). The full ranking results are shown in Fig. 4, in which the dotted line labeled "PL" (Pareto line) represents the threshold defined by the GR20%.

Fig. 4 also shows that categories "Project" (C2) and "Political" (C6) each have three risks within GR20%, quantities notably greater than the other categories. By Eq. (17), it is noted that the fuzzy weight $\tilde{w}_k^C$ of categories weights the probability-impact multiplication of risks. If a ranking was developed only from $\tilde{w}_k^C$ for relative importance between categories, C2 and C6 would emerge as the first and second places in such a ranking, which can explain their predominance in the LRP. This fact reveals not only the impact, but also the influence that $\tilde{w}_k^C$ has on the final results of risk weights by the FAHP presented.

In 2016, the Brazilian Federal Court of Auditors (TCU) audited 126 public constructions throughout the country, and the most frequent irregularities verified were related to contract flaws, overpricing, overbilling, and design deficiencies (TCU 2016). All four issues pointed out by TCU are, respectively, consequences and direct effects of risks R9, R11, R37, R14, and R12. These five risks are within the GR20%, that is, above the PL. This fact contributes not only to the validation of the developed LRP but also to support the assumption that 20% of the risks may be responsible for 80% of the problems and barriers in achieving the goals of public enterprises in Brazil.

The LRP reveals that "Difficulty in environmental licensing" (R54) is the main risk assessed by this research. Complex and strict environmental licensing processes such as the Brazilian processes (World Bank 2008) are usually associated with many problems due low efficiency, slowness, bureaucracy, and encumbrance on the public and private sectors.

The second main risk—"Design changes during construction" (R14)—primarily derives from two sources: variations demanded by clients and design shortcomings (Taylan et al. 2014). According to the authors, the first source may concern changes in initial assumptions established for project scope because of changes of mind or misunderstanding of the action plan by the client, that is, the public contracting party. In consequence, it is important to establish a skilled project team as early as possible in order to set the scope of project and its role accurately. The second source is directly linked to the risk "Design errors" (R12), the last risk above the PL. Inappropriate and insufficient designs can lead to imprecise construction budgets and schedules. Hence, construction projects carried out based on defective designs may result in the waste of money and time, because both design and specification changes may be necessary throughout construction (Kuo and Lu 2013). It should be noted that impacts on project goals will be lower the earlier changes are made (PMI 2013).

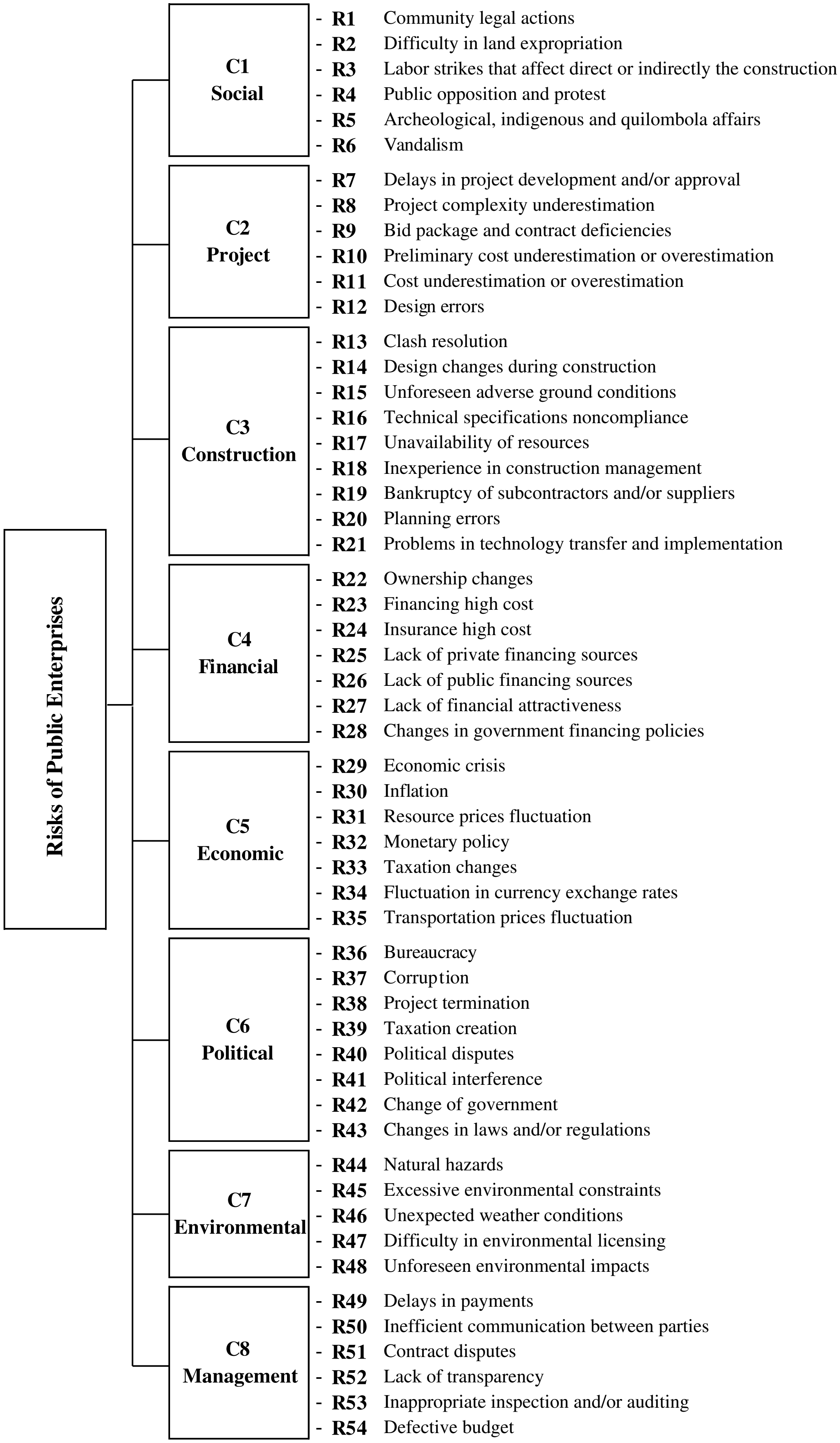


Fig. 3. RBS of Brazilian public enterprises.

Table 4. List of risks prioritization

Risk code	Category code	Category name	$\tilde{w}_i^R$	w_i^R	W_i (%)	Ranking (degrees)
R47	C7	Environmental	(0.0013, 0.0149, 0.1497)	0.055	7.33	1
R14	C3	Construction	(0.0008, 0.0122, 0.1398)	0.051	6.75	2
R37	C6	Political	(0.0005, 0.0083, 0.1337)	0.048	6.30	3
R9	C2	Project	(0.0006, 0.0076, 0.1154)	0.041	5.46	4
R2	C1	Social	(0.0009, 0.0078, 0.0822)	0.030	4.01	5
R29	C5	Economic	(0.0005, 0.0061, 0.0767)	0.028	3.68	6
R36	C6	Political	(0.0004, 0.0049, 0.0730)	0.026	3.45	7
R41	C6	Political	(0.0003, 0.0056, 0.0719)	0.026	3.43	8
R11	C2	Project	(0.0003, 0.0050, 0.0714)	0.026	3.39	9
R51	C8	Management	(0.0004, 0.0051, 0.0646)	0.023	3.10	10
R12	C2	Project	(0.0003, 0.0044, 0.0608)	0.022	2.89	11
...	...	...	...	...	...	...
R21	C3	Construction	(0.0000, 0.0001, 0.0013)	0.0005	0.06	54

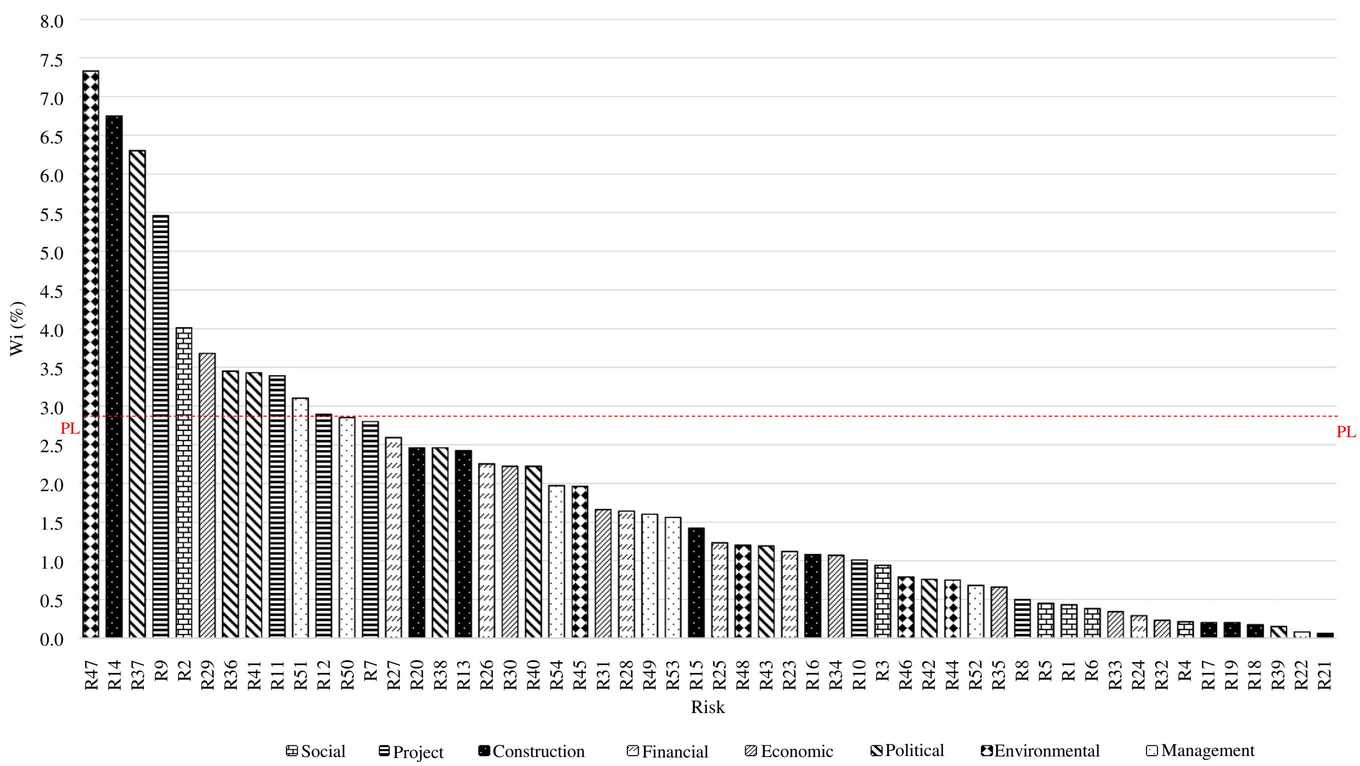


Fig. 4. Graphic presentation of the LRP.

Amid the biggest operation against corruption in Brazil's history—Operation Car Wash—the risk "Corruption" (R37) was more than expected to feature among the major risks on the list. Corruption has become an inherent part of Brazilian public enterprises' procurement and undertaking during the last decades, particularly in infrastructure projects (Signor et al. 2016). Indeed, corruption is a pervasive stigma in the construction industry in many countries (Bowen et al. 2012). Therefore, investigating its causes and vulnerabilities is essential in order to address this widespread issue in the construction sector (Le et al. 2014). Misappropriation due to corruption is derived mainly from bribery, fraud, collusion, embezzlement, nepotism, and extortion (Chan and Owusu 2017).

Concerning the risk "Bid package and contract deficiencies" (R9), even if bid package documents do not present any flaws, the bid contract established after the bidding process can be flawed. Hence, a mutual understanding between the public and private parties of the variables and clauses in bid contracts is essential to the success of construction projects (Bu-Qammaz et al. 2009).

"Difficulty in land expropriation" (R2) is usually a result of legal disputes during the expropriation of lands declared as public interest. These disputes are mainly due to disagreements about the indemnity fee or are a result of litigation between parties.

"Economic crisis" (R29) can unchain, direct or indirectly, the other risks in the "Economic" category. Economic crisis usually induces an increase in inflation rates, which, in turn, results in resource and transportation price fluctuations. In addition, economic crisis can raise the basis for calculating taxes, leading to fluctuations in currency exchange rates. The consequences of an economic crisis are broad and not limited to the illustrated events, having the potential to significantly affect success criteria with regard to the cost of a public construction.

Table 5. Comparison with research worldwide

References	Sector/country	Category code	Risk code
Zayed et al. (2008)	Highway project/China	C2, C3, C4, C5, C6, C7	R47, R51, R12
Bu-Qammaz et al. (2009)	Expressway project/China	—	R9, R23, R36
Li and Zou (2011)	International construction project/Turkey	—	R47, R2, R36, R12
Nieto-Morote and Ruz-Vila (2011)	Building rehabilitation project/Colombia	C2, C3	R14, R12
Yang and Wei (2011)	Highway project/China	C2, C3, C5, C6, C7	—
Kuo and Lu (2013)	Metropolitan construction/Taiwan	C1, C2, C3, C5, C7	R14
Taylan et al. (2014)	Building project/Saudi Arabia	—	R47, R14, R37, R36, R51, R12
Boateng et al. (2015)	Infrastructure megaproject/Scotland	C1, C2, C3, C5, C6, C7	R41, R51, R12
Elbarkouky et al. (2016)	Project contingency/Canada	C8	—
Liu et al. (2016)	International construction project/China	C1, C2, C5, C6	—

"Bureaucracy" (R36) is a frequent complaint from companies hired to undertake public enterprises, mainly related to excessive approval procedures. The government can contribute significantly to the mitigation of this risk by alleviating the number of documents (e.g., technical capacity certificates, liquidity certificates, environmental licenses, and so on) required to secure that companies are qualified enough to carry out the construction (Taylan et al. 2014). Nevertheless, contractors can also play an important role in managing this risk.

"Political interference" (R41) originates from agents that act aiming to politically influence decisions that they are not liable for. This risk is related to political opposition and indecision, in addition to lack of political support. Among the most common causes, the political clout that public enterprises can carry due their importance to the population in terms of problem solving should be highlighted. As a result, strategic public constructions to address certain demands can be objects of political conflict and collision.

The risk "Cost underestimation or overestimation" (R37) as one of the GR20% underlines the fact that knowledge about potential flaws in the cost estimation process is a key factor in minimizing the negative impacts of inefficient budgets.

Finally, "Contract disputes" (R51) are more likely to occur in constructions that involve earthmoving and soil conditions (e.g., highways, basic sanitation projects, tunnels, and river channeling projects). Moreover, a bidding process based on lowest price, regardless of its being the most traditional practice in the construction industry, increases the possibility of disputes (Ballesteros-Pérez et al. 2016). Choosing the winning bidder according to the best value has arisen in contrast to the lowest price practice; this allows criteria such as technique, quality, and price to be balanced with each other to form a ranking that allows the selection of the most worthwhile proposal (Ballesteros-Pérez et al. 2015).

Although risk analysis is directly related to context (ISO 2009), there are some similarities with other studies that have prioritized construction risks. The categories defined by the brainstorming panelists for the RBS were also observed in seven studies (Table 5). Categories C2, C3, C5, C6, and C7 were suggested by at least four of these studies. Category C1 was used by three studies, whereas Categories C4 and C8 were employed by only one research each. Table 5 also exhibits a comparison with prioritizations presented by different studies worldwide. R12 is common to almost all prioritizations, being one of the main risks in five out of seven studies. In practice, proper designs are fundamental to achieving enterprise goals successfully, because the quality of drawings is a key factor in accomplishing lasting constructions built within cost and on schedule. R47, R14, R36, and R51 were priorities for three studies, whereas R37, R9, R2, R29, and R41 were highlighted by only one study each. R11 did not appear as a major risk in any of the studies. Concerning the Brazil, Russia, India, China, and South Africa (BRICS) scenario, it can be noted that seven risks of the GR20% (i.e., R47, R14, R9, R29, R36, R51, and R12) were also verified in the Chinese construction context.

Conclusions

This research attempted to elicit major construction risks and prioritize these risks by the FAHP model presented, with respect to Brazilian public enterprises. The results and discussion enable the authors to conclude that the FAHP presented is a reliable and accessible tool for risk prioritization in situations in which input data is either scarce or inadequate. Nevertheless, it relies on participants' expertise and knowledge about the project assessed. Some FAHP gaps in practical risk analysis were addressed as follows: (1) adjustment of the FAHP proposed by Hsieh et al. (2004) to the risk analysis context, considering risk as a product of its probability and impact; (2) consistency analysis of matrices as stated by Saaty and Tran (2007); and (3) the practicality of solving the equations presented in this study, which were all computed using spreadsheets.

The case study enabled four important insights with regard to the framework presented for the assessment of construction risks. First, it was noted that category weights significantly influence the final results of the prioritization, because they weigh the product between the probability and the impact of the risks. Consequently, special attention should be given to the pairwise comparisons of categories. Second, it may be tricky to achieve $\mathrm{CR} \leq 0,10$ even after reassessing pairwise comparisons due the considerable effort and time it demands from specialists. Therefore, it is necessary to deepen the concept of consistency with experts before they begin their comparisons. Third, it is difficult to ensure that risks of the same category are mutually independent, but comparable. This fact is evident when analyzing the category "Economic": its main risk—"Economic crisis"—can trigger, direct or indirectly, the other risks in the category. Fuzzy analytic network process (FANP) may aid in overcoming this issue, because it takes into account such interdependencies. Fourth, different RBSs can lead to different priority rankings for the same set of risks, because pairwise comparisons are carried out only between risks within the same category. Thus, the LRP developed in this research uniquely concerns the categorization carried out by the brainstorming panelists.

It is believed that the significance of this research is broad and not restricted to Brazil because (1) a comprehensive list of risks of public construction ventures was identified entirely from studies concerning different countries and can therefore be used to support risk assessment worldwide; (2) the FAHP framework presented can be adapted and implemented in various construction projects, whether public or private; and (3) the categories used in the RBS can provide insights into possible risks categorization. Moreover, because the GR20% risks were verified in other studies, the LRP

J. Constr. Eng. Manage., 2019, 145(2): 05018018

developed can provide guidance for construction risk analysis, particularly in developing countries due to contextual similarities with Brazil. Therefore, this research provides relevant information that contributes to the global body of knowledge related to construction risk management.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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