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RISK ANALYSIS

KEYWORDS
Risk Management • Risk Factors • Analytic Hierarchy Process • Monte Carlo Simulation • Construction Projects.

Experts' Engagement in Risk Analysis: A MODEL MERGING ANALYTIC HIERARCHY Process and Monte Carlo Simulation

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• ABSTRACT •

This paper presents a risk analysis model merging Analytic Hierarchy Process (AHP) and Monte Carlo simulation (MCS) that enables risk prioritization, providing a contingent cost analysis. The model has six steps: risk factors definition; risk frequency prioritization using the AHP; probability estimation for risk effects; probability distribution for other variabilities; correlation analysis between cost and time; and MCS for cost estimation. The proposed model was applied to 12 industrial wastewater projects. Data were gathered from interviews and documents. The results show three major contributions: a decision tool to identify, analyze and assess the risks, experts' engagement (knowledge and perception), and visual output for risk analysis.

1. INTRODUCTION

Low productivity in the construction industry, particularly in infrastructure, transportation, sanitation, and energy projects, hinders economic growth in developing countries. One of the main causes of this inefficiency is that significant numbers of risk factors are not considered in the planning process (Odimabo & Oduoza, 2013). The increasing complexity and dynamism of construction projects (Nieto-Morote & Ruz-Vila, 2011), characterized by intensive technologies, high investment (Liu, Jin, Xie, & Skitmore, 2017) and many stakeholders (Shen, 1997), turn risk management particularly relevant.

Several studies pointed out that the lack of risk management contributes to increased costs and extended deadlines of construction projects (Boateng, Chen, & Ogunlana, 2015; Brookes, 2014; Chan, Chan, Lam, Yeung, & Chan, 2011; Flyvbjerg, 2014; Nasirzadeh, Khanzadi, & Rezaie, 2014; Zhao, Hwang, & Yu, 2013), affecting project success (Baloi & Price, 2003; Berssaneti & Carvalho, 2015). For large and complex infrastructure projects involving high costs and stringent deadlines, neglecting risk management generates considerable loss (Touran & Lopez, 2006) particularly to investors (Liu et al., 2017). Despite the extensive research conducted in this field, there is a gap concerning the analysis and identification of risks in the early phases of such projects (Albogamy & Dawood, 2015). Moreover, most contractors face strong challenges when putting risk management into practice in construction projects (Baloi & Price, 2003), related to the lack of high quality data of historical record (Liu, Li, & Wang, 2013).

The traditional risk frameworks are based on experiential, subjective and implicit knowledge (Khazaeni, Khanzadi, & Afshar, 2012). Zhang (2011) recognizes that "project characteristics (such as temporariness and novelty) and organizational conditions (such as lack of relevant databases) usually make the subjective estimation of risk probability ambiguous". In addition, for complex projects, the probability of some risk occurrence is difficult if not impossible to predict (Thamhain, 2013).

In fact, by using direct probabilities, important uncertainty aspects could easily be overlooked (Aven, 2010) and reliability validity criteria of for risk assessment cannot be met (Aven, 2016). For instance, the conventional way of using probability in project management does not observe the interactions or interdependencies between different risks (Iyer & Sagheer, 2010).

Several papers have shown that this difficulty can be addressed by the Monte Carlo simulation (MCS). This model allows to consider the uncertainty that affects projects (Liou, Huang, & Chen, 2012; Carbonara, Costantino, & Pellegrino, 2014; Dutra, Ribeiro, & Carvalho 2014), and to obtain information about the expected behavior of the project (Acebes, Pajares, Galán, & López-Paredes, 2014; Acebes, Pereda, Poza, Pajares, & Galán, 2015). Also, the efficiency of controlling a project can be measured using a MCS (Vanhoucke, 2012; Acebes et al., 2015), as well as financial evaluation (Hanaoka & Palapus, 2012).

However, the soft side of risk management should also not be neglected (Carvalho & Rabechini, 2015). For dealing with subjective judgement, there is an increasing use of the fuzzy sets theory and Analytic Hierarchy Process (AHP) (Khazaeni et al., 2012; Liu et al., 2013; Nieto-Morote & Ruz-Vila, 2011), incorporating subjective judgements, knowledge and experience acquired from many experts in risk management in a structured way.

Although the conventional process of risk analysis may be adequate for small projects, it presents limitations for large and complex projects, that needs effective management (Carvalho, Patah, & Bido, 2015; Qazi, Quigley, Dickson, & Kirytopoulos, 2016) and in which risks correlate and interfere with project goals in a different manner (Pech & Ribeiro, 2013). Another significant factor is that traditional models also need quantitative information, which is not available in most construction projects (Taroun, 2014).

In this context, this paper aims to narrow the research gap proposing a risk analysis model that merges AHP and MCS.

Some studies have used AHP to prioritize risk factors (Albogamy & Dawood, 2015; Dey, 2002; Mustafa & Al-Bahar, 1991; Zayed, Amer, & Pan, 2008; Zhao, Lei, Zuo, & Zillante, 2010). However, most assessments employ the term "importance" (a vague reference parameter), while the model proposes a substitution of the term for AHP rank, which is executed by investigating the risk occurrence frequency in previous projects. Besides, MCS is used to obtain the distribution cost curve. To demonstrate the applicability of the proposed model, industrial wastewater treatment plant projects were used as case studies.

This paper is organized as follows. Firstly, we present the literature background on risk in construction projects. Then, we introduce the research model. After that, we present the case studies results, applying the proposed model, followed by the discussions and conclusions of the study.

2. LITERATURE REVIEW

--- 2.1 Risks in construction projects ---

Risk identification and analysis during engineering project stages play a significant role in decreasing imperfections and inaccuracies in their schedule and budget (Albogamy & Dawood, 2015), and are critical for decision making process (Wang & Yuan, 2011). Such risks often correlate (Wu & Mao, 2015) and affect a project, causing delays and additional costs. Zhao et al. (2010) showed that lack of timely and effective communication, absence of integration, changes in context, and high project complexity are the most common causes of change in construction. These authors argue that predicting causes related to additional costs is arduous and costly and its consequences are difficult to control. However, management teams must appropriately anticipate such causes at engineering project stages (Zhao et al., 2010).

Considerable uncertainty also makes it difficult to obtain information on items vital for cost estimation: climatic and environmental conditions, adequate construction methods, clients' financing capacity, and construction complexity (Chou et al., 2013). Similar conclusions were drawn by Dey (2002) using AHP to prioritize several construction risks of an oil pipeline in India, concluding that the most relevant are technical and scope-related changes.

Technical planning is an important factor for making the best decisions concerning the costs and risks of project development, particularly in engineering designs. The documentation development process should be prioritized for being essential for the cost estimation (Chou et al., 2013).

This suggests that critical risks are present at the initial phases of technical projects, in which a contractor's participation is highly required. Namely, the client's lack of construction experience, designer's errors, and faulty coordination among authorities may compromise the expected project results (Albogamy & Dawood, 2015). Similarly, the high complexity of infrastructural projects can cause typical deviations in specifications hindering the construction process (Zavadskas, Turskis, & Tamošaitiene, 2010).

Some risk factors are important in the construction project context, such as estimate-related, design-related, level of competition, fraudulent practices, construction-related, economics-related, and politics-related (Baloi & Price, 2003). Others, such as human factors play a significant role for the construction practitioners (Whang, Xu et al., 2016). Zou, Zhang, and Wang (2007) identified engineering project risks factors based on the stakeholders' points of view. Research results based on the answers of 83 surveys on the Chinese construction industry demonstrated that 25 major risk factors grouped into 6 factors stood out: risk related to clients, risk related to designers, risks related to contractors, risk related to subcontractors/suppliers, risk related to government agencies, and external issues. Other risk factors, such as damage to commercial interests of local communities, damage to habitat, and financial crisis are identified more recently as significant factors in infrastructure projects (Wang, Wang, Zhang, Huang, & Li, 2016).

Chapman (2001) developed a method to examine the influence of risk factors on identification procedures and threat assessment during the engineering project phase taking as a reference unprecedented engineering solution, innovative design, lack of planning information, noncompliant document format, poor liaison with local authorities, delayed information provision, and inadequate scope definition.

El-Kholy (2015) analyzed 40 construction projects in Egypt and concluded that additional costs are strongly correlated with identified risk factors. The research prioritized 44 risks obtained from the literature and used the first 11 to determine this dependence. Among them, two belong to engineering project stages: faulty technical documentation and delayed delivery of drawings and specifications.

In China, research on road construction risks conducted by Zayed et al. (2008) revealed that during previous work stages, projects face certain risks such as delayed completion of technical documents, mistake correction, amendment requests, and unpredicted soil conditions. Indeed, these factors increase a project overall risk if the technical documentation quality remains inadequate throughout the execution (Zayed et al., 2008).

--- 2.2 Analytic Hierarchy Process and Monte Carlo simulation in risk frameworks ---

Although AHP has been used in various fields, a relatively fewer number of applications are observed in project management, and these applications are found only in a few sectors (Subramanian & Ramanathan, 2012). Thus, this model aims to expand this domain.

In the early years of AHP development, risk analysis appeared to be a promising field for its application, mostly to identify the best decision-making strategies in situations of uncertainty (Mustafa & Al-Bahar, 1991; Saaty, 1987). Mustafa and Al-Bahar (1991) applied AHP to investigate the risk level of construction projects and established relative values for three risk levels: high total risk; medium total risk; and low total risk. The study used risk sources as criteria of AHP and risks as its subcriteria. Risks identified and considered in the model were financial (subcontractors' bankruptcy, fund unavailability, and inflation); political (civil instability, sabotage, changes in public policies, embargoes, and expropriations); and force majeure (floods, earthquakes, fire, and climate changes).

Accordingly, Millet and Wedley (2002) proposed a risk model using AHP. The authors used case studies and estimated the relative likelihood of the calculation of expected values. Instead of using absolute probability (virtually impossible to estimate and a major barrier in project risk management), the authors used normalized weights of AHP as the relative likelihood of risk and labeled this parameter as "subjective absolute probability."

A study developed by Dey (2002) used AHP to analyze risk probability in construction projects in India, combined with a decision tree to spot the best response alternative to risk reduction.

The high risks of major highway Chinese constructions were evaluated using AHP in a model based on two main threat areas: company (macro) and project (micro) (Zayed et al., 2008). Comparison of results using AHP revealed that political risks are the most important followed by financial ones for the macro case. For the micro case, the main risks were new technology and resources.

International construction project risks were investigated using AHP to evaluate risk factors, considering political, economic, cultural, and technical/construction, among other categories (Chen & Wang, 2009). Wang et al. (2016) also proposed a risk assessment framework based on an adapted Analytic Hierarchy Process (AHP) in major infrastructure projects. Funo, Muniz, and Marins (2013) investigated how critical risk factors are for the supply chain of the major national manufacturer using AHP in the aerospace industry in Brazil.

The use of AHP combined with the Fuzzy Set Theory has increased (Buckley, Feuring, & Hayashi, 2001; Chen & Sanguansat, 2011; Chen & Cheng, 2009; Kuo, 2013). For instance, Chou et al. (2013) developed a model for decision-making support in bidding processes. It classifies factors according to the additional cost they cause, thus estimating their importance. In addition, MCS produces a probability curve used as a strategic tool to quantify project risks and to calculate offers value in construction project bids (Chou et al., 2013). Liu et al. (2013) proposed a fuzzy synthetic evaluation approach for risk assessment, in which AHP/ANP is used to determine sensible weights of each criterion to evaluate individual and overall risks. Khazaeni et al. (2012) integrated the fuzzy logic qualitative approach and the AHP adaptive capabilities to evaluate allocation of project risks. Nieto-Morote and Ruz-Vila (2011) also presented a risk assessment method based on the Fuzzy Sets Theory for subjective judgement, and AHP to structure a large number of risks, incorporating knowledge and experience acquired from many experts.

Thus, AHP has been characterized as a useful tool in risk analysis, prioritization, and evaluation. However, in the studies investigated, it is not entirely clear whether the parameter "importance" was attributed to the probability, impact, or to both during the evaluation.

The MCS has been used to take into account the uncertainty that affects a project (Carbonara et al. 2014), sometimes combined with AHP. Considering the relevance of risk management in the early phases of large projects, Albogamy and Dawood (2015) used AHP to evaluate the importance of risk factors related to clients during project design. Risk factors were defined as criteria in AHP. The authors employed MCS with AHP-obtained results to calculate the duration of a construction project. Hanaoka and Palapus (2012) proposed a method using MCS for financial evaluation. Vanhoucke (2012) proposed the efficiency of controlling a project is measured and evaluated using a MCS study on fictitious and empirical project data. Acebes et al. (2015) proposed a model based on the Earned Value Methodology and risk analysis, using extensive MCS to obtain information about the expected behavior of the project.

3. RESEARCH MODEL

This section presents a risk analysis model merging AHP and MCS that enables risk prioritization as input uncertainties, providing an analysis of expected costs in distinctive scenarios, based on experts' inputs.

--- 3.1 Model overview ---

The model was developed in six steps, as shown in Figure 1

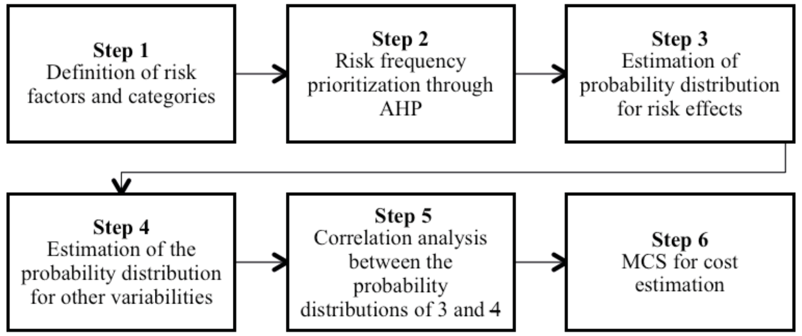

FIGURE 01. Six phases of the model

Step 1 starts by defining risk categories from experts' collaboration, incorporating their knowledge in a systematic way. For each risk category, we identified relevant risk factors based on experts' inputs and analyzed the content of project documents. Particularly, the risk sources responsible for negative consequences (e.g., rework, unnecessary procedures, failures in deliverables, and interruptions in the project development) that will lead the project to exceed its cost are discussed with experts. As a result, step 1 provides the risk breakdown structure (RBS). In step 2, after the previous qualitative analysis, the risk factors are prioritized according to the experts' evaluation using the frequency of risk occurrence as an AHP parameter. Impacts are considered subsequently. Step 3 furthers AHP by comparing the levels of risk effects in relation to each risk factor. This way, the probability of each impact level is calculated by AHP results. These probability values form the discrete probability distribution then inputted in MCS (Step 6). Step 4 defines probability distribution for other relevant variabilities (e.g., duration of activities, price of materials, and contextual conditions). Step 5 investigates if correlations exist between levels of risk effects and the other relevant variabilities, analyzing appropriate parameters and developing distinctive scenarios. Data provided by steps 1 to 5 are then inputted in step 6 to determine the probability distribution of total costs with risk effects using MCS.

--- 3.2 Risks frequency and risk effects: application of AHP ---

The model here proposed uses AHP in steps 2 and 3. This process, developed in the 1970s by Thomas L. Saaty (Saaty, 1977, 1980), provides an adaptable and comprehensive tool to help people, projects, and companies make complex decisions. AHP is a multiple criteria decision method, in which evaluation parameters are established in hierarchical levels such that several criteria aid in decision-making. In our case, we use the RBS. AHP has been used in various fields (Subramanian & Ramanathan, 2012), mostly when quantitative and qualitative components are needed for analysis. Its application reveals the relative values of decision options, comparing the suitability of alternatives. The application of this method includes a hierarchical dissection of a problem based on criteria, subcriteria, and alternatives to decision making. Subsequently, the experts on the subject matter are appointed. These professionals are responsible for three evaluations: (a) pairwise comparison of criteria (here, risk categories); (b) pairwise comparison of subcriteria (here, risk factors); and (c) pairwise comparison of decision-making alternatives (here, risk effects) for each subcriterion.

The method is based on the construction of reciprocal matrices A^w (n x n) in which binary judgments are elements a_{ij}^w, with $a_{ji}^w=1/a_{ij}^w$. Matrix consistency is thus a crucial aspect, for example, if alternative α is twice as important as alternative β and alternative β is four times as γ; α must be eight times more important than γ. In other words, considering that A^w is completely consistent, we have $a_{ij}^w \; a_{jk}^w=1/a_{ki}^w$ for each i, j e k ≤ n. Hence, as Saaty (1980) demonstrates, the prioritization of decision parameters is given by relative values determined by the eigenvector of A^w equivalent to its highest eigenvalue. The fundamental axioms of the method were presented by Saaty in two studies, which mathematically guided the method (Saaty, 1986, 1991).

The relative probability of risk effects explained in the previous subsection is estimated by pairwise comparison using AHP. In this model, the evaluations should be performed with specialists separately, in face-to-face interviews. When implementing the AHP, the expertise level of the group is more important than the number of people. As this study, others have also used small groups for judging the AHP (e.g., Zayed et al., 2008; Dey, 2002; Liu et al., 2013). Evaluation is conducted with the assessment group, using relative frequency as a parameter.

The question to experts in step 2 is: *Considering your experience in projects with these characteristics, which of these two risks has happened more frequently? and, in step 3: The occurrence of risk factor X (the risk factors identified in step 1) may generate which of the two levels of effect?* Thus, the probability distribution of risk effects results from the normalization of the indices prioritization obtained post AHP application.

This method uses a scale with linguistic variables adapted from Saaty's model (1980), ranging from ⑨ extremely most frequent to ① equally frequent. This way, the value of each risk factor represents its relative probability (Dey, 2012). The evaluation performed 'face to face' prevents personal opinion from influencing others (Saaty & Vargas, 2007). For the group result, the geometric average of jury members in each evaluation is used (Saaty & Vargas, 2007).

4. RESEARCH MODEL APPLICATION METHOD

--- 4.1 Experts and projects sampling and data collection ---

To test our model, theoretical sampling was adopted for applying the research model by examining 12 replicated cases (Eisenhardt & Graebner, 2007). All the experts participate in engineering projects in industrial wastewater treatment plants (IWTP), water (WTP), and sewage (STP) in Brazil.

In Brazil, the national bidding law states that all construction projects must undergo certain stages prior to execution: basic engineering design (BED) and detailed engineering design (DED). This refers to a phase in engineering in which all technical documents, such as drawings, specifications, descriptive memorial, and physical and financial schedules, are developed (TCU, 2013). This phase generates a reference documentation project (RDP) whose details will be explained in the following sections.

For applying the research model, 12 BED and DED processes in IWTP, WTP, and STP projects were analyzed in-depth through interviews and document analysis. The interviews were conducted with six management-level professionals working within the largest project companies, national and multinational. The profile of these specialists is presented in **Table 1.**

All the experts have over 8 years of experience in large projects. The budget of these projects ranges between U$ 1 and U$ 6 billion. The project phase relating to BED and DED documentation ranges from U$100 to U$300 million.

	Gender	Experience (years)	Role	Education	BED and DED costs (USD million)	Company size	
Cost estimation experts	M	27	Project manager	Civil Engineering	100 - 200	Large/medium	
	M	14	Proposal coordinator	Industrial Design	200 - 300	Large	
	M	20	Director	M.S. in Civil Engineering	100 - 300	Medium	
	F	25	Project manager	Bachelor's and M.S. in Chemical Engineering	100 - 200	Large/medium	AHP Evaluators
	M	10	Construction planning coordinator	Civil Engineering and MBA in Project Management	100 - 300	Large	
	M	22	Instrument engineer	Electronic Technologist	100 - 300	Medium/small	
	M	18	Electric engineer	Electric Engineering	100 - 300	Small	
	F	10	Project manager	Chemical Engineering and MBA in Management and Quality	100 - 300	Medium/small	
	F	9	Quality supervisor	MBA in Environmental Technology and Management	100 - 300	Medium	
	M	15	Process coordinator	Chemical Engineering and Petrochemical Postgraduate	100 - 200	Large/medium	
	M	12	Consultant	PhD in Physics and MBA in Project Management	100 - 200	Large/medium	
	F	8	Project engineer	Bachelor's and M.S. in Chemical Engineering and MBA in Project Management	100 - 300	Large/medium	

TABLE 01. Expert profiles and projects characteristics

Face-to-face interviews with each of these experts were conducted and project documents analyzed. The research instruments investigate the risk categories and risks factors based on a list extracted from recent literature. Besides, several questions to understand aspects of risk processes were included, as to how a commercial proposal is elaborated, i.e., how to estimate: the amount of technical documentation; the document cost; the relation between this cost and the executor's profile; the risks and contingency provision, and the rework costs of documentation reviews. Other subjects refer to cost control during project execution and improvement of the engineering process to reduce project rework.

--- 4.2 Step 1 - Definition of risk breakdown structure: categories and factors ---

The RBS, deployed in risk categories and risks factors were determined by content analysis of the experts' experience in BED and DED documentation. In our study, these are the main causes of additional costs in this type of projects. Table 2 schematically presents the categories and risk factors mentioned in this section with their corresponding codes.

Category	Code	Risk Factor
Communication Failures	LCS	Lack of stakeholder communication
	LIC	Lack of interdisciplinary communication
	LID	Lack of internal discipline communication
Scope Failures	PDS	Poorly defined and/or understood scope
	SCE	Scope exclusion
	SCI	Scope inclusion
Professionals' Mistakes	IPE	Inattention of the performer employee
	ENE	unexperienced employee
	PIM	Personal interests of managers
Quality Defects	LCR	Lack of customer rules
	LIE	Lack of internal and external procedures
	LTP	Lack of training in internal procedures

TABLE 02. Risks categories and risk factors in basic engineering design (BED) and detailed engineering design (DED)

Frequent risks are related to the lack of communication between stakeholders, which may be internal to a specific engineering discipline or cross-disciplinary. The underlying reason being that technical documentation originates from a team of professionals who collectively develop the project foundations. Risks related to changes in scope are also frequent in early phases. These can originate from scope flaws (Tran & Molenaar, 2014) or from lack of relevant information unavailable to stakeholders (Ward & Chapman, 2008; Zavadskas et al., 2010). This research also indicates that the profile, expertise and ability of managers and other staff shape the final technical documentation. Specifically, the lack of necessary focus and detail at each step of document preparation, lack of expertise, reviews and experience may add costs to the process. Finally, another relevant source of failures occurs during the document implementation process, related to the non-compliance of internal and external procedures previously tested, used and standardized by the companies (Chapman, 2006). Thus, these risks may change the project design several times, causing additional costs and delays in its schedule.

After the interviews, the critical aspect was to determine the causes and costs of rework in the early stages of process planning. In fact, the documentation generated through BED and DED guided the entire project implementation process. Moreover, low-quality documents prepared via these steps or the absence of important elements of these records would negatively affect an entire project. Essentially, in this case, rework manifests itself in a high number of reissued documents for being uncoordinated with specifications or its purposes. Costs associated with systematical reissues indicate process failures, which are often spotted at a late phase, thus aggravating work execution. Thus, this case study aims to identify the risks of these reissuances, and thus quantitatively assess the additional costs generated by them.

The topics covered, and their major results, are as follows: (i) Technical documents: quantity estimation – experts considered that the quantity of documents must be estimated from the preliminary layout and customer specifications. Three experts emphasized that some customers demand a great quantity of documents. The assessment group considered the background of the proposed team, evaluation of project complexity, and its limits to be crucial for this estimation; (ii) Technical documents: cost estimation – experts informed that the estimated cost of documentation considers the average time and the average cost for its preparation. This time can be estimated from the lessons learned in other projects. Average cost is calculated considering the direct costs (e.g., labor), and indirect costs (e.g., software, administrative index). According to the group, risk analysis is important for this calculation; (iii) Dependency between documentation execution cost and professionals involved in the project – all the experts stated that cost of the technical documentation is defined by the average cost of the professionals involved in the project implementation; (iv) Evaluation of contract type, project risks, and rework costs – all the experts stated that their companies performed contract and risk analysis. A manager informed that when rework is risk-related, it is added to a project's contingency cost provision. Another expert informed that a critical analysis is performed post project acquisition to ensure both budget and deadline are faultless. Four experts reported the importance of checking against previous projects to clarify possible queries during the bid phase to avoid rework; (v) Contingency index calculation – they confirmed to have a contingency index. Five of them stated that it is based on previous experiences and project budget but solely for short-term projects. An expert considered that such an index must be calculated by a risk analysis. It is therefore clear that companies mostly follow past experiences rather than quantitative methods for risk analysis. The contingency cost is determined using all the BED and DED documentation project; (vi) Labor cost control and comparison of budgeted and realized value – all companies confirmed the significance of the control of hours worked and planned. According to an expert, a comparison between actual and planned durations is performed for their direct link to costs. An expert warns that hours given to specialists and senior engineers must be more carefully controlled because these may extrapolate costs. Finally, a manager reported that companies tolerate a cost variance of 10% and that a contract is issued for revised labor costs if that value is exceeded (claim); (vii) Process improvement to reduce rework costs – the assessment group suggested that efforts related to communication protocols, scope, quality, and personnel management improve the engineering process. Main improvements regarding scope regard its accurate preparation and control during execution. Note that contractual management suitable to both clients and suppliers is crucial to maintain scope. Regarding communication, it is important to maintain the team integration by adopting a strong and interactive process. Regarding quality, we must improve engineering processes and implement quality management. Finally, the assessment group broached the topic of personnel management. They reported that successful BED and DED developments essentially depend on the close monitoring of work execution, understanding individual staff limitations, and adequate personnel's profile assessment, which facilitates the allocation of responsibility. Note, also, that the use of interactive software may ease to deal with repetitive documents.

Based on the information obtained from the research conducted, the cost estimate (C) of BED and DED without rework can be equated as follows:

$$C = \sum_{j=1}^{m} n^j \sum_{i=1}^{l} x_i^j \, y_i \; ; \qquad (1)$$

where n^j is the number of type j documents; m is the number of different types of documents; x_i^j and y_i are the time (in hours) spent in the preparation of document j by professional category i, and the professional's hour-value i, respectively. l is the number of professional categories assigned to a project. For a realistic estimation, considering rework, the total project cost (C_T) must be calculated by C_T= C+ C_R, where C_R is the reissue cost of documents given by

$$C_R = \sum_{k=1}^{p} r^k \sum_{i=1}^{l} x_i^k \, f_i \, y_i \; ; \qquad (2)$$

Here, r^k is the amount of reissue of document k, p is the total number of project documents, and x_i^k f_i is the time (in hours) spent in reissuing document k, calculated from its issuance duration x_i^k multiplied by f_i, a correction factor for reissues. The values attributed to f_i are discussed further in this section.

--- 4.3 Step 2 and 3: Application of AHP to estimate the reissue probability distribution ---

In this research, the application of AHP aims to estimate the discrete probability distribution for the quantity of reissues of each BED and DED document type. The evaluations were performed with 9 specialists, separately, in face-to-face interviews (see Table 1).

First, to prioritize the categories and risk factors pointed out in the previous section, the application of step 2 of our model was performed, posing the following question to the experts: Considering your experience in BED and DED projects, which of these two risks has happened more frequently?

After that, it was assumed that the number of reissued documents can be standardized in three levels: low emission, medium emission, and high emission. The amount of reissues for each level depends of document kind, in the following way: Designs, 2, 3, and 6; Specifications, 2, 3, and 4; Data Sheets, 2, 4, and6; Lists of materials, 2, 4, and 6; Description memorials, 2, 3, and 4; Calculation memorials, 2, 3, and 4, respectively.

Then, in the application of step 3 of the model proposed herein, we used the following question: Which of the two amounts of reissuing may the occurrence of risk factor X (X = LCS, LIC, etc) generate?

In summary, in this model, the frequency in which a risk category manifests in process planning is considered a AHP prioritization criterion, and the frequency of risk factor, the subcriteria. Following the AHP terminology, alternatives to be prioritized are the additional emission levels (high, medium and low). The structure developed in this case study is represented in Figure 2.

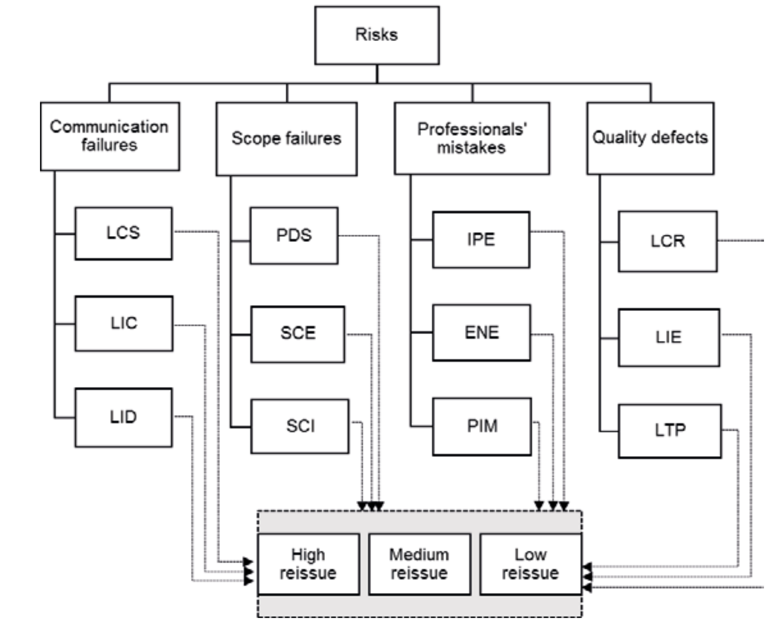

FIGURE 02. Risks: hierarchical structure

Therefore, the probability distribution of the quantity of reissues will results from the normalization of the indices prioritization obtained post AHP application.

--- 4.4 Step 4 to 6: Cost estimate of BED and DED with MCS ---

MCS has been an effective technique to study the cost of construction projects and, together with the AHP has been used in several applications (Yaraghi, Tabesh, Guan, & Zhuang, 2015). Indeed, these techniques were combined to analyze situations in which quantitative and qualitative aspects of uncertainty cannot be overlooked. In this work, we used MCS to analyze BED and DED cost. This corresponds to steps 4 to 6 of the proposed model. We consider input variables the probability distribution for r^k (amount of document reissues) and for x_i (work production time per each staff category). Notice that, in this case, MCS also uses as input the cost distribution of delays of each delivered document.

The lack of control might lead to repeated document production and, thus, noncompliance with deadlines and budget. This model application aims to analyze the causes that generate the project risks of this rework and to quantify its possible consequences. To this end, we elaborated a reference project of an industrial wastewater treatment plant using 557 documents, called RDP. All the information contained in RDP was obtained from research on real projects developed by major Brazilian companies that carry out projects in this area. All the quantitative results yielded will be generated from the data used in the RDP.

The development of RDP was based on interviews with the assessment group, cost charts and schedules used by companies executing IWTP, WTP and STP projects. Its values follow the standards and proportions used in actual projects (ABNT, 2011). The duration of individual document preparation and the professionals' profiles were defined via interviews. Although designers and engineers take turns at executing some documents, quality assurance specialists mandatorily participate in the control of each document, requiring the same time, regardless of the document type. Their work is routinely associated with creating production guidelines and uploading those documents to the digital platform used by the client. Thereby, for quality purposes, factor f included in Eq.2 was equaled to 1. For engineers and designers, the data indicated that f should equal 0.5, instead.

Table 3 presents several items used in the simulation. For r^k, we used discrete distribution probability, as reported in the previous subsection, whereas Pert distribution (Albogamy & Dawood, 2015) with quantities obtained from concrete spreadsheets was adopted for x_i. In this Pert distribution, the best case represents a 15% decrease of the most probable value and the worst case, a 40% increase. The results of C,C_R and C_T are estimated by Eqs. (1) e (2), whose values are given in thousands of R$ in Table 3, for a random iteration.

5. RESEARCH MODEL RESULTS DISCUSSION

--- 5.1 Risk categories ---

The expert evaluators' feedback demonstrated that Communication Failures is the most frequent category, with a relative value of 0.5385, followed by Scope Failures, with 0.2196. That is, Communication Failures happen twice as much as Scope Failures, showing that a high interaction between stakeholders is required to conclude the process with quality, as suggested by other authors (Barlow, 2000; Hwang, Zhao, & Toh, 2014; Wang & Huang, 2006). The group's score was extracted from the expert evaluators' geometric average for each assessment.

--- 5.2 Risk factors ---

The experts' analysis revealed that the most frequent factors are: Lack of communication with stakeholders (LCS = 0.2466); Lack of interdisciplinary communication (LIC = 0.2240); and Poorly defined and/or understood scope (PDS = 0.1438). These results corroborate previous research (De Bakker, Boonstra, & Wortmann, 2011; Yang & Zou, 2014). This shows the perception of a high degree of occurrence of ineffective communication. SCE, ENE and LIE resulted in the lowest values among most experts, indicating that they have the lowest occurrence frequency.

--- 5.3 Reissue rate ---

As explained in previous subsections, the reissue rate of documents was obtained by AHP based on the prioritization of the alternatives: low, medium and high reissue. Evaluation here refers to the expected quantity of reissued documents against the occurrence of a given risk factor. With the frequency investigated in previous evaluation steps, we can now estimate the probabilities for each reissue level. The results for the group are: 40% high, 40% medium, and 20% low, revealing that several risk factors, which have higher occurrence frequency, are also responsible for the largest share of reissues. We used these rates given by the model application as input data to calculate the probability distribution of rework costs. The results of these calculations are presented in the following subsection.

--- 5.4 Cost of technical documentation ---

The results from the previous sections were applied in RDP to obtain the final cost distribution of BED and DED. As the RDP portrays what happens in projects developed in this area, these results may provide an indicative of the actual additional cost due to reissue and documentation delay.

Simulations were performed by @Risk version 7.0 (Palisade, 2014) using 2200 repetitions, which sufficed to achieve convergence with 3% tolerance and 95% certainty. Figure 3a presents the probability distribution for the total cost of the technical documentation of the RDP, which has 557 documents elaborated according to definitions and standards dictated by engineering. The expected value (or mean) of C_T equals 5.44 million, and the standard deviation 79.946 (given in R$). Adjustment was executed by Gaussian distribution, which, among others tested, proved to be the best function.

The probability distribution for C_R is presented in Figure 3b. Document reissue, with all the associated delays, represents a considerable portion of the total cost. If we analyze the mean value, 35% of the total cost refers to rework and, if we analyze percentile 90, the percentage is 36%. In other words, the lack of efficient actions which reduce identified risks, intolerably multiplies the cost variation range.

To quantitatively reveal how the model behaves, two scenarios were developed (SCE Ω and SCE Ψ) assuming that risk evaluation (generated by AHP) would be implemented after the main risk factors (LCS, LIC, and PDC) were mitigated in a company, as shown in **Figure 4**. For example: (i) adopting the appropriate mode (im/personal) and frequency of communication for each stakeholder type (Turkulainen, Aaltonen, & Lohikoski, 2015); (ii) establishing an efficient communication scheme among the designers (Zou et al., 2007); and/or (iii) using of "stakeholder analysis," "communication requirements analysis," and the communication process (Chou & Yang, 2012) addressed in the PMBOK® Guide (PMI, 2012).

It was thus expected that, in this case, the most frequent risks would not imply a high reissue of documents, with AHP results decreasing high-reissue rates whilst increasing the low-reissue ones. SCE Ω represents the probability inversion between high and low reissue whereas SCE Ψ depicts a more radical change, with mitigation processes already institutionalized. This model considered a change in percentage for the high and low probabilities between SCE Ψ and SCE Ω equal to the change in percentage between SCE Ω and the original.

The probability distribution of the number of reissued documents for the three scenarios screen output is also presented in Figure 4. The replacement of high-output probability for low-output probability (SCE Original → SCE Ω) shifts the distribution curve by 320 reissues, in the negative horizontal axis direction. In the case of SCE Ψ, the curve reveals an even greater mitigation with the same number of reissues, portraying the result of effective risk treatment.

AREAS	TYPE OF DOCUMENTS	n	r^k	x(hour)			xf(hour)			C_T (R$ thousand)	C_R(R$ thousand)
				x_1	x_2	x_3	x_1f_1	x_2f_2	x_3f_3		
ARCHITECTURAL	DESIGN - PLAN	1	2	6.70	21.99	1.00	2.61	10.03	0.74	8.29	1.96
CIVIL	DESIGN - DIM AND LOADS	1	2	3.82	13.69	0.65	2.26	7.72	0.68	5.79	1.56
ELETRICAL	CALCULATION MEMORIAL	1	2	19.40	0.00	0.89	12.86	0.00	0.70	7.95	2.27
HVAC	DESCRIPTION MEMORIAL	1	2	7.04	35.92	0.88	4.59	17.45	0.64	13.07	3.33
INSTRUMENTATION	SPECIFICATION	1	3	21.58	0.00	0.79	10.14	0.00	0.67	9.18	3.61
MECHANICAL	MECHANICAL SPECIFICATION	1	1	22.01	0.00	0.83	12.09	0.00	0.72	5.99	0.00
PROCESS	DATA SHEET - TANK	1	1	15.94	0.00	0.71	8.41	0.00	0.90	4.33	0.00
SMS	PIPE LIST FROM FIRE SYSTEMS	1	5	23.27	0.00	0.77	8.94	0.00	0.94	12.21	6.53
PIPE	DESIGN - BASIC ARRANG PIPE	1	2	28.30	0.00	0.73	18.35	0.00	0.67	11.32	3.20
ARCHITECTURAL	DESIGN - PLAN	1	2	3.30	11.23	0.74	1.49	6.24	0.81	4.71	1.23
CIVIL	DESIGN - PLAN AND DETAILS	1	5	3.14	12.13	0.69	1.40	5.28	0.61	7.63	4.23
ELETRICAL	LIST OF MATERIAL	1	5	18.06	0.00	0.81	10.28	0.00	0.80	12.39	7.37
HVAC	CALCULATION MEMORIAL	1	2	34.81	0.00	0.75	21.63	0.00	0.98	13.62	3.80
INSTRUMENTATION	SPECIFICATION	1	3	17.72	0.00	0.65	8.87	0.00	0.68	7.87	3.18
MECHANICAL	DATA SHEET - PUMPS	1	2	33.62	0.00	0.67	14.71	0.00	0.77	11.00	2.59
PROCESS	VALVE LIST	1	5	44.66	0.00	0.76	18.32	0.00	0.67	23.70	12.80
SMS	DATA SHEET - SAFETY ITEMS	1	3	10.35	0.00	0.72	6.00	0.00	0.83	5.20	2.23
PIPE	MATERIAL REQUEST	1	3	10.02	0.00	0.80	4.98	0.00	0.73	4.59	1.86
									Total	5,435.00	1,966.00

TABLE 03. Cost calculation spreadsheet

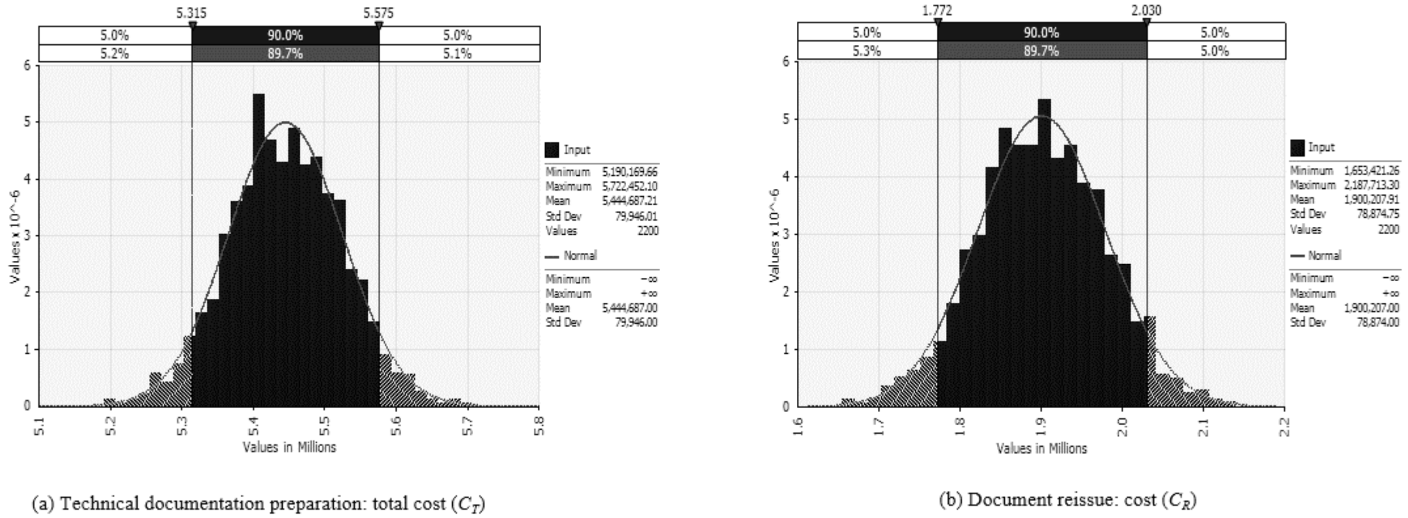

FIGURE 03. Cost simulation in MCS

6. CONCLUSION

This paper presents three major contributions. First, it proposes a model merging AHP and MCS that can be used as a decision tool to identify, to analyze and to assess the risks. Second, the approach involves experts in the whole process applying visual tools; in the beginning, by gathering knowledge and experience to identify risk categories, risk factors and build the RBS and, during the process, to

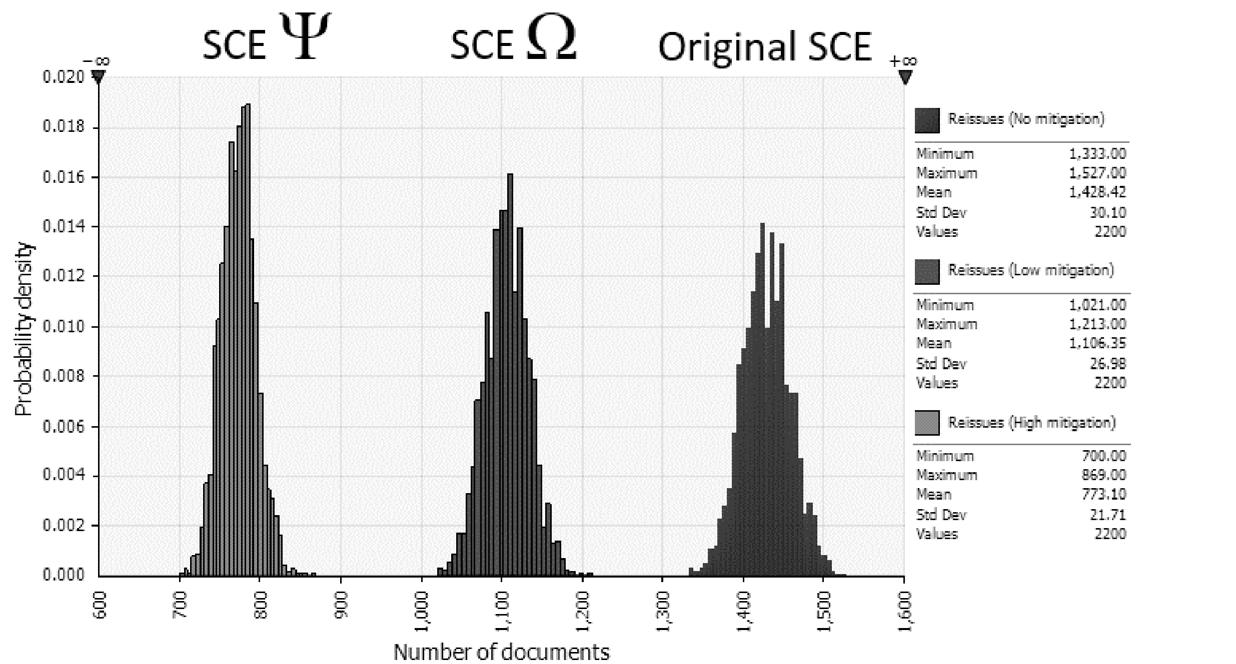

FIGURE 04. Risk mitigation: scenarios

discuss the scenarios and to identify other key variables that can affect risk analysis. Third, it provides a six-step systematic approach for risk analysis that integrates qualitative and quantitative approaches, using several sources of evidences, such as interviews and document analysis.

This paper also has managerial implications because the model can help the organizational decision-making process as it reveals the roots of different problems and its impact in a visual and participative way. The model application also helps to understand and to estimate costs more adequately in an engineering project by foreseeing irreparable damages. Besides, a RBS for BED and DED projects is presented and can be used as a template for project management in this kind of project, exploring four categorized communication failures, scope failures, professionals' mistakes, and quality defects, which could help. The most critical categories pointed out were communication failures and scope failures. The critical factors identified were the lack of communication with stakeholder lack of interdisciplinary communication, poorly defined and/or understood scope.

This paper presents limitations related to the methodological choices. First, for the surveyed companies, experts and projects are from the same type and same country, which limited the generalization of the application of results. However, different types of project can follow the proposed model because experts, according to their experience and knowledge, can customize the application. The model application in other countries or other organizational cultures would reveal discrepancies that would enhance the analysis. ◆

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