UTS ePRESS

Construction Economics and Building

Vol. 18, No. 2
June 2018

Citation: Paz, J. C., Rozenboim, D., Cuadros, Á., Cano, S. and Escobar, J. W. 2018. A Simulation-Based Scheduling Methodology for Construction Projects Considering the Potential Impacts of Delay Risks. *Construction Economics and Building*, 18:2, 41-69. http://dx.doi.org/10.5130/AJCEB.v18i2.5842

ISSN 2204-9029 | Published by UTS ePRESS | ajceb.epress.lib.uts.edu.au

RESEARCH ARTICLE

A Simulation-Based Scheduling Methodology for Construction Projects Considering the Potential Impacts of Delay Risks

Juan Camilo Paz[1], David Rozenboim[2], Álvaro Cuadros[2], Sandra Cano[2], John Willmer Escobar[3]*

[1] Department of Civil and Industrial Engineering, Pontificia Universidad Javeriana Cali, Cali, Colombia.
[2] School of Industrial Engineering, Universidad del Valle, Cali, Colombia.
[3] Pontificia Universidad Javeriana Cali, Cali, Colombia.

***Corresponding author:** John Willmer Escobar, Pontificia Universidad Javeriana Cali, Cali, Colombia, E – mail. jwescobar@javerianacali.edu.com

DOI: http://dx.doi.org/10.5130/AJCEB.v18i2.5842
Article History: Received 27/11/2017; Revised 02/05/2018 & 22/05/2018; Accepted 27/05/2018; Published 27/06/2018

Abstract

This paper tackles the problem of scheduling construction projects considering the influence of delay risks. In the actual body of knowledge, several methods have been proposed to handle this problem, starting from the Project Evaluation and Review Technique to advanced simulation models. However, this investigation proposes a novel integration of one methodology with some approaches already existing in the literature related to Monte Carlo Simulation scheduling techniques as seen from the perspective of a practitioner. The research began with a literature review of both schedule risks and Monte Carlo based scheduling models for construction projects. Based on this, the methodology was designed with the constant participation of experts in the construction industry. As result of this, a comprehensive and practical methodology was constructed. Therefore, a new mathematical structure for the simulation model within the methodology was formulated in which a new concept for each risk defined as "potential impact" was used. Moreover, the simulation model is based on the judgment of experts and methods of the known literature such as the explicit model of the occurrence probability of the risks and the activity-risk factor matrix. Then, to validate the tool, the proposed methodology was applied using the information of an already constructed construction project of a public university of Colombia. The obtained results

DECLARATION OF CONFLICTING INTEREST The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. **FUNDING** The author(s) received no financial support for the research, authorship, and/or publication of this article.

were a confidence-based forecast of the end date of the project and a quantitative importance measure of the modelled risks. These results were compared against the real history of the project since it was found an excellent performance of the proposed methodology. To sum up, the research process described above supports the validity of the proposed methodology.

Keywords

Construction, Monte Carlo simulation, project management, risk analysis, scheduling.

Introduction

Risks affecting construction projects impact different indicators of success. Among them, it is possible to mention: the quality, the sufficiency of the scope, the social environment, the technical functionality, the security requirements, the foreseen term of execution, and the assigned budget (Ökmen and Öztaş, 2008). Traditionally, time, cost and quality have been the predominant successful criteria of construction projects (Chan and Chan, 2004). For these different indicators, the timely completion of contracted obligations is important for assuring the success of the project. Indeed, a project could be economically unfeasible due to the application of some penalties for excess time and cost and the lack of quality of the tasks. Also, a delay in the construction works could, in many ways, affect all stakeholders, such as the owner, the government, the companies, the workers and the users (El-Sayegh, 2008).

Different perspectives have been considered to deal with the challenge of risk management on projects (Flanagan and Norman, 1993; Uzzafer, 2010; Dikmen, Birgönül and Arikan, 2004). In particular, the Project Management Institute (PMI, 2008) has formulated risk management as a systematic process of identification, analysis and answer to the risks of projects. This process is divided into six steps: i) planning of management of risks, ii) identification of risks, iii) qualitative risks analysis, iv) quantitative risks analysis, v) responsive plans and vi) control and monitoring of the risks. As can be seen, it is a relevant field the study of risks effects on the schedule of construction projects. In fact, there is extensive literature review such as Kolisch and Hartmann (2006) and Hartmann and Briskorn (2010).

Therefore, it is essential to establish a comprehensive, accurate and objective schedule technique that considers the risk effects to support the construction project risk management, and thus contribute to these projects' successes. Traditionally, the Critical Path Method (CPM) has been widely used for scheduling construction projects. However, the most noticeable weakness of this technique is the consideration of deterministic values for the activities' durations (Antill and Woodhead, 1990), which ignores changes caused by the influence of risk factors. Thus, several techniques have been developed. One of the first approaches was the Program Evaluation and Review Technique (PERT). This method has weaknesses already discussed in the literature; for example, Tysiak (2011), affirm that PERT approach is nothing else than an application of the CPM to estimate a normal distribution of the project duration afterwards; ignoring, the fact that there is no unique critical path and that the critical path changes from case to case (Ökmen and Öztaş, 2008). Additionally, very often PERT only use beta distributions for the individual activities, and the normal distribution for the result is criticized (Tysiak, 2011). Nordmeyer (2018) presents some additional disadvantages of the use of PERT charts related to their subjective analysis (the process of PERT method is subjectively generating a chart that does not calculate the estimation of time and costs accurately), with their time focus (PERT approach is considered primarily as a time-focused method) and with their resource intensity (PERT method requires a detailed analysis involving many people from different organizations becoming an expensive approach to support). Furthermore, the PERT does not allow implementation of a range of existing constraints in the execution of projects.

On the other hand, there exists an extensively researched technique that could address the gaps discussed above, better than the traditional scheduling techniques; this is the Monte Carlo Simulation (MCS) (Ökmen and Öztaş, 2008; Tysiak, 2011). The MCS has addressed the scheduling of construction projects from different perspectives. In this research, a literature review concerning these models was carried out by review of 15 models that combine MCS with different scheduling techniques. However, all of them have different ways to model the effect of risk on the schedule, advantages and disadvantages, and model various considerations of the reality. In this context, this paper deals with the problem of how to analyse the impact of risks in the schedule of construction projects using a Monte Carlo Simulation-Based Scheduling Methodology (SBSM).

Unlike previously published works, the proposed SBSM approach models the risk impact only for critical activities. Furthermore, this paper addresses the scheduling problem of construction projects by proposing the concept of "direct impact" of risks. Indeed, for each risk, minimal, most probable, and maximum impacts are defined. These values represent a measure of the effect of the risks on the total duration of the project. In addition, the mathematical relation between risks and activities was included. Based on this concept, as well as the integration of other powerful characteristics found in several models of the literature, an SBSM has been developed to numerically value the effect of the risks on the schedule of a construction project. The proposed model supports the quantitative analysis of risks and has been tested with real data obtained from a construction project of a medical building at a public university in Colombia. This new SBSM was designed to achieve two primary objectives; first, to determine the end date of the project, and secondly, to determine a quantitative measure of the risks' importance. The results guarantee: i) the use of practical tools from the perspective of expert practitioners, ii) the use of expert judgment due to a probable lack of information and iii) the research limited to the study of "delay risks". The last mentioned is understood as the risks that could prolong the end date of construction projects (Ökmen and Öztaş, 2008).

The main contribution of this work is the methodological and mathematical structure proposed to perform a quantitative risk analysis on the scheduling of construction projects. Indeed, the proposed approach uses an MCS model with a new mathematical formulation to represent the effect of the delay risks on the duration of the schedule. Also, all the elements of the SBSM have been defined in such a way that the effort of the activity programmer is simplified. This issue provides the possibility of obtaining a schedule risk analysis model. Additionally, experts in the construction sector supported the proposed structures for the design and validation phases to guarantee an applicative focus. For all these reasons, the proposed model establishes a new scheme to represent the effect of the delay risks on the duration of a construction project. Also, a literature review was undertaken, identifying the different schedule risks to which construction projects are exposed. In this sense, this paper contributes to the literature review related to the identification of the construction risks.

Research Method

The proposed research methodology is based on a deductive method, which allows generalization of a specific case to the SBSM approach for construction projects. A scheme that allows visualizing the methods used and the relationship between them is shown in Figure 1. Note that methods such as consultation with experts and analysis to build the SBSM scheme have been considered. Afterwards, the SBSM is tested. This process was performed based on data from a construction project of a public university in Colombia for which, first, the SBSM was applied to project the date of completion and criticality of the project's risks. And then, the predictions of the SBSM were compared against the real history of the project.

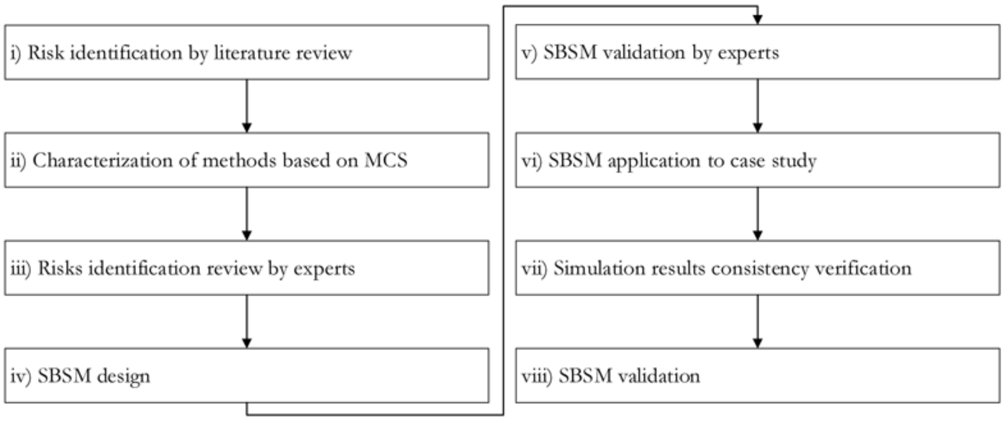

Figure 1 Steps of the research method

A more detailed description of the steps of the methodological process of the research is the following:

i. 13 research articles identifying 471 risks to which the construction projects are exposed were reviewed.
ii. 15 research articles on models and methodologies to apply the MCS to the analysis of program risks in construction projects; achieving a characterization of the methods regarding their advantages and disadvantages of application were studied.
iii. Two experts from the construction sector were consulted to analyse the risks found in i). The risks that are not applicable to the Colombian context were eliminated. Also, those risks that did not affect the project's program were taken out of consideration. Based on this, the list of risks applicable to the study context was defined.
iv. A methodological proposal that could be applied to the resources available in the construction sector was proposed. This approach allows a reasonable level of prediction regarding the date of completion of the project and the measurement of the importance of risks.
v. A consultation was performed with four experts from the construction sector for analysing the revised methods of the literature, and the methodological approach initially proposed. These revisions were performed until it was determined that the resources demanded by the tool were feasible to provide the SBSM methodology in a real application environment. The analysis of resources such as the available data, the judgments of consulted experts, the feasibility of carrying out the calculations of a real project and the permissibility in time of execution of the steps of the tool were considered.

vi. An application of the methodology to a case study of a project already built was performed. The computational experiments were conducted under the supervision of managers belonging to the owner of the project, guaranteeing that the professionals involved were not aware of the history of the project under study.
vii. The results of the simulation carried out in the framework of the SBSM were replicated three times by changing the seed of the series of the random values. This process allows verification that the series used not affect the results obtained.
viii. Finally, a comparison was performed between the results of the application of the SBSM proposed against the real history of the project. This process was performed to validate the effectiveness of the SBSM based on the closeness between the model's prediction and the real outcome.

The literature review was performed to consider studies of the risks that affect the scheduling program as well as the methods of risk analysis that use MCS as a basis. Also, the risks were limited to the project of the case of study (Colombia). However, these limitations respond to the need to generate results consistent with the environment of the case study.

Literature Review

Vanhoucke (2012) defines project planning as a prominent area within Operations Research, which aims to mathematically determine the beginning and the ending times of the project activities by considering precedence and resource constraints. Specifically, project planning optimizes a determined objective as the total execution time of the project. Early research was oriented towards the development of linear programming models; then, there were developed network techniques, such as PERT and CPM, still widely recognized as essential tools and project management techniques. Currently, a significant amount of research has been conducted in different areas of project scheduling (for example schedule, resource scheduling and programming costs). Literature on project baseline scheduling can be found in the overview papers written by Brucker et al. (1999), Herroelen, De Reyck and Demeulemeester (1998), Icmeli, Selcuk Erenguk and Zappe (1993), Kolisch and Padman (2001), Özdamar and Uslusoy (1995), Kolisch and Hartmann (2006) and Hartmann and Briskorn (2010).

On the other hand, the risk management in projects has been developed from different perspectives. For example, Barry Boehm proposed a risk management model divided into two steps, the risk evaluation and the risk control (Uzzafer, 2010). Furthermore, Dikmen, Birgönül and Arikan (2004) cited by Ökmen and Öztaş (2008), defined the risk management of the project as a systematic process to control the risks identified with anticipation. Also, it was described as a step-by-step procedure consisting of the identification, classification, analysis and definition of responses to risks (Flanagan and Norman, 1993).

In this field of study, there are some research projects oriented to identify and to classify the risks that affect construction projects; this aspect is the first step performed before the consideration of a risk analysis. For example, Assaf and Al-Hejji (2006) grouped the most significant risk factors that cause delays in construction projects, which have been discussed in several scientific journals and technical reports. In that classification, the following factors were considered: the project, the project managers, the contractors, the consultants, the design, the workforce, the machinery and the environment.

In this research, a characterization of schedule risks is performed. This aspect was carried out to establish the risks for the SBSM methodology. A summary of the most significant papers in the topic is presented in Table 1. In this review, 471 causes of delays were identified. However, the importance given to these risks is relative to the context where the surveys were performed; for example, one project could be affected by the effects of high temperatures of the weather such as in Saudi Arabia, but that fact is not applicable in the Colombian framework. Therefore, they were not taken as the identified risks for the starting point of the SBSM. Instead, a systematic process was developed to extract from these articles the relevant risks for the Colombian context, explained in further detail in the SBSM application section.

Note that scheduling and risk management in projects is a prominent research area. However, network techniques such as the CPM method use deterministic values for activities duration without considering changes caused by the influence of risk factors. Nevertheless, it is evident that some risks could affect the execution of specific activities of projects and their duration. This is one of the reasons for promoting the development of new scheduling models seeking integration between the quantitative assessment of risks and traditional project scheduling. Indeed, these quantitative tools have been included in the project risks management process. Specifically, the theoretical framework proposed by the PMI provides for the application of these types of tools as part of their risk management process "quantitative risk analysis" (PMI, 2008).

In the literature reviewed, there are several developments of tools related in some manner with the quantitative analysis of schedule risks. These approaches provide information about the risk factors' sensitivity, the correlation effects into the programs of construction and other aspects. All of this is done with the purpose of supporting the development of response strategies against risks (Ökmen and Öztaş, 2008). Some of these models are: Model for Uncertainty Determination (MUD) (Carr, 1979), Project Duration Forecast (PRODUF) (Ahuja and Nandakumar, 1985), PLATFORM (Levitt and Kunz, 1985), Conditional Value of an Expected Model (CEV) (Ranasinghe and Russell, 1992), Accurate Simulation (Touran and Wiser, 1992), Factors Simulation (Woolery and Crandall, 2000) and Networks Under Correlated Uncertainty (NETCOR) (Wang and Demsetz, 2000).

Table 1 Relevant literature related to risk factors

Paper	Country	Year	Number of risks
Zhi	China	1995	58
Kangari	EE.UU	1995	26
Chan and Kumaraswamy	China	1997	20
Ahmed et al.	China	1999	26
Kartam and Kartam	Kuwait	2001	26
Odeh and Battaineh	Jordan	2002	28
Wang, Dutaimi and Aguria	Singapore	2004	28
Assaf and Al-Hejji	Saudi Arabia	2006	70
Andi	Indonesia	2006	27
Ling and Hoi	India	2006	5
El-Sayegh	United Arab Emirates	2008	42
Luu, Sthiannopkao and Kim	Vietnam	2009	16
Aziz	Egypt	2013	99

More recently, Nasirzadeh, Khanzadi and Rezaie (2014) presented an integrated fuzzy-system dynamics approach for quantitative risk allocation. Risk analysis has also been considered with methods such multi-criteria tools (Dey, 2010). Zhang and Chu (2011) proposed approaches that consider the judgment involved with risk factors using the Analytic Hierarchy Process (AHP), or the fuzzy failure mode and the effects analysis for project risks. In this work, methodology that integrates risk prioritization with the probability, impact and possibility of risk, is introduced. Other interesting approaches are the optimization algorithms used for minimizing risk in projects (Zafra-Cabeza, Ridao and Camacho, 2004; and recently Waledzik and Mandziuk, 2017).

Moreover, among the existing tools, there are some based on MCS. This technique can incorporate the stochastic nature of activity and risks in the scheduling process of construction projects. Additionally, it gives researchers a flexible way to model different aspects related to risk analysis in the scheduling process; for example, the mathematical method to describe activities with risks. In this paper, a scheduling methodology, based on MCS is proposed. In line with this, the subsequently literature review is limited to tools or methodological structures for quantitative risk analysis that involves the scheduling of construction projects using MCS. A summary of the most significant papers on the topic is presented in Table 2. In this table, the reviewed works are compared with the proposed SBSM of this paper.

Most methods for schedule risk analysis in construction projects consider the uncertainty of activities' duration to calculate the competition probability of a project through simulation process. For instance, Zhong, Liu, and Yang (2005) combined network planning simulation techniques and risk analysis to calculate the project completion probability.

One relevant model is the Judgmental Risk Analysis Process (JRAP) proposed by Öztaş and Ökmen (2005). This model allows determination of the variation of the duration of the activities in the construction project schedule by using expert judgment and MCS. Finally, the same authors presented another methodology - Correlated Schedule Risk Analysis Model (CSRAM) which takes into account the correlation between risk factors (Ökmen and Öztaş, 2008). The proposed methodological structure of the CSRAM is summarized in the following steps: i) define the network diagram (activities, precedence relationships), the minimum, expected, and maximum durations, ii) identify risks and their correlations, iii) define degrees of influence of the risk factors by activity, iv) define limits of probability of the state of the risk factor and v) model and execute the simulation.

Table 2 Comparison between simulation-based scheduling methodologies

	Risk factors analysis		Details of the risk analysis			
Studies	Qualitative analysis	Quantitative analysis	Consider uncertainty of activities duration	Consider the correlation between risk factors and activities	Consider the modelling of the uncertainty of risk factors	Consider the potential impact risk factors
Oztas and Okmen (2004)	✓	✓	✓	✓		
Oztas and Okman (2005)	✓	✓	✓	✓		

Table 2 continued

	Risk factors analysis		Details of the risk analysis			
Studies	Qualitative analysis	Quantitative analysis	Consider uncertainty of activities duration	Consider the correlation between risk factors and activities	Consider the modelling of the uncertainty of risk factors	Consider the potential impact risk factors
Zhong et al.(2005)			✓			
Kwak and Ingall (2007)			✓			
Bowman (2007)			✓			
Okmen and Oztas (2008)	✓	✓	✓	✓		
Wallace (2010)		✓	✓	✓	✓	
Jun and El-Rayes (2011)			✓			
Dikmen et al. (2012)		✓	✓	✓	✓	
Wang et al. (2012)			✓			
Choundhry et al. (2014)	✓	✓	✓	✓		
Zhong et al. (2015)		✓	✓	✓	✓	
Zhong et al. (2016)		✓	✓	✓	✓	
Yuan (2017)		✓	✓	✓		
This Paper	✓	✓	✓	✓	✓	✓

Kwak and Ingall (2007) used MCS to quantify the effects of risk and uncertainty in project schedules and budgets, to get a statistical indicator of project performance, like target project completion date and budget. In the same way, Bowman (2007) using a program evaluation and review technique (PERT) and proposed a method that estimates the effects of changes to the probability distribution for any activity time on several project schedule measures, such as the probability of meeting a specified due date and a project (penalty) cost function.

Wallace (2010), proposes a practical approach based on the MS Project software with three characteristics: i) uses the CPM to calculate the duration of the activities, ii) defines an "impact" for each risk and iii) considers a probability of occurrence explicitly in the model. The model ignores the most probable, the maximum, and the minimum, duration for each activity. The effect of the risks in the overall duration of the project is evaluated for each scenario by simulating when a risk has occurred. If the risk occurs in the scenario, an impact is generated to each activity according to with the risk.

Jun and El-Rayes (2011) presented a fast, and accurate, approximation method using the PERT and MC simulation to focus the risk analysis on the most significant paths in the project network by identifying and removing insignificant paths that are either highly correlated or have a high probability of completion time in large construction projects. Wang et al. (2012) proposed a MC simulation method that allows easy identification of the critical path and the most critical activity in PERT network. In the same line of research, Choundhry et al. (2014) used MC to analyse the risks and the real completion date in a bridge construction project in Pakistan.

Furthermore, Dikmen et al. (2012) developed a web tool to predict indicators of a construction project such as the cost and duration. The tool uses MCS with the risk assessment model based on cost-duration influence diagram proposed by Poh and Tah (2006) for construction projects.

Zhong et al. (2016) present an improved CSRAM that involves underground powerhouse construction simulation based on the Markov Chain Monte Carlo (MCMC) method. This approach considers the interrelationship between the states of parameters through a Markov state transition probability matrix and the set model of a time buffer to absorb the effect of potential disturbances. On the other hand, Yuan et al. (2017) combined MC simulation with Building Information Modelling (BIM) to establish a method that considers a scale of warning boundaries according to the project risk probability. This proposal considers simulating the schedule every time an activity finishes so that the risk probability can be estimated, and the warning scale can be used. In that way, the method addresses the logical relationship between construction activities and visually implements early warning according to construction-duration probability.

In synthesis, each structure proposed in Table 2 defines a point of view that depends on several factors as the required by the depth of the analysis, the level of the representation of the reality, the complexity of each project and the possible difficulties obtaining the input data.

In general, the works proposed by Ökmen and Öztaş (2008), Öztaş and Ökmen (2004, 2005) assume that risk is the only source of variation of the activity duration of a construction project. In the work of Wallace (2010), the author proposed methodology that uses judgmental data obtained from experts and implicitly includes the effects of risks of the durations of activities and their forecasts, in the author simulation model. In the work of Öztaş and Ökmen (2005), a pessimistic point of view is maintained, (all risk effects are unfavourable), and the risks-activity relations are modelled in a direct way regarding a percentage that indicates the proportion that risk can impact over the duration of an activity. Finally, Ökmen and Öztaş (2008), present considerable improvements regarding the methodology JRAP (Öztaş and Ökmen, 2005), including: greater simplicity of the input data, an improvement in the adaptation of relations of the variables, and a different vision about the estimation of the duration of the activities that considers the favourable and unfavourable effects of the risks. The simplification of the data input is related to the new definition of the relationship between risk-activity. Indeed, this relationship is no longer defined as a percentage, but it is defined as a qualitative scale that is translated into a numeric value. Additionally, the correlation between risks is calculated implicitly.

The elements of the proposed SBSM approach were obtained of the information described above. The proposed SBSM includes from the CSRAM (Ökmen and Öztaş, 2008) the risk-activity relation matrix. This technique implies a qualitative qualification by the expert, of influence between risks and activities, in a qualitative scale of very effective, effective, and ineffective. The matrix of criteria is transformed into a numeric value representing the rate of an influence of a risk factor into one activity. Also, the proposed methodological structure includes from Wallace (2010) the explicit definition of an occurrence probability and impact for each risk. Also, the SMSM proposed in this paper differs from works like the one described by Öztaş and Ökmen (2004) because the risk impact is not modelled for each risk-activity relation; instead, it is only modelled for critical activities. Finally, a potential impact for each risk is defined within the proposed SBSM approach.

Indeed, for each risk a minimal impact, most probable, and maximum impact, are defined; values that represent for the consulted experts, a measure of days of the effect of this risk on the project activities. Included as well, is the mathematical relation to use this definition to model the relation between risks and activities.

Proposed Simulation-Based Scheduling Methodology for Construction Projects

The SBSM, as well as it mathematical structure for MCS, is described below (see Figure 2). The proposed methodology allows the evaluation of active networks under uncertainty, by using MCS (stochastic model). This is done to determine the total time of termination of the project, considering the direct impact of the risks. The proposed methodology considers three elements; i) the definition of a potential impact on the overall duration of the project for every risk, ii) the assumption that risks are the only agents of change of activity durations and iii) the requirements of the constructions projects to obtain the data practically. This methodology contains four steps, (from D to G), for which the mathematical model is described in the step G and defined by sets, parameters, input variables, variables, and the mathematical formulas which represent the effects of delay risks in the project schedule.

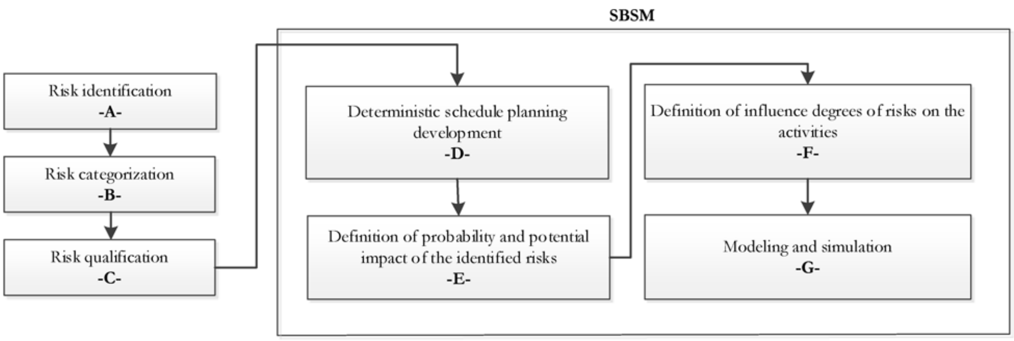

Figure 2 Steps of the SBSM

In step A, the objective is to consolidate a list of all the risks to which the project can be exposed. This process aims to generate a starting point for the quantitative analysis. Therefore, according to Galway (2004), it is possible to use techniques such as literature review, brainstorming, the Delphi method and SWOT analysis. In step B, the risks are classified, to identify which interest groups are the primary source of risk; this information could help the subsequent postulation of strategies to face the risks; a classification that can be used for this purpose is the one proposed by El-Sayegh (2008). In step C, qualitative tools are used to perform a first filter, due to the importance of the list of risks obtained in step A. There are multiple techniques in the literature to perform this type of analysis (Carbone and Tippet, 2004; El-Sayegh, 2008; Dey, 2010; Zhang and Chou, 2011).

Described in the section 'Results and Discussion', is how these steps were carried out in the investigation for replicability effects. However, the steps A, B, and C are essential for the SBSM approach. These steps are considered as a reference for the approach and not as something fixed to be performed. Therefore, other techniques could be used within the framework of the SBSM. This is explained by the fact that in the literature review it was possible to verify that each construction environment should be carried out with these studies and that it is not correct to generalize the identification, categorization and qualification of the risks. Furthermore, to identify, categorize and qualify risks, there are multiple tools in the literature.

Step D is related to the elaboration of the deterministic schedule planning. In this step, the deterministic model of the project is built by defining the activities, precedencies, and postpositions, and deterministic durations.

In step E, a probability of occurrence must be assigned to the most important risks that can affect the project (step F). This probability could be based on the experience of experts, taking as reference the amount of spent time for each risk on similar projects. Also, a potential impact of risks that can generate the risks onto any important activity must be defined regarding a minimal, more probable, and maximum duration. These parameters are used to model the impact of risks through a triangular probability distribution. This potential impact is not expressed by considering particularities of the project as the precedence constraints of the activities or the critical path. Instead, it is a point of reference of the impact that each risk may have on the activity duration of the project.

In step F, the degrees of influence of the risks on the activities selected by the experts are defined using two qualitative qualifications: "very effective" or "effective". This scale is considered from CSRAM model proposed by Ökmen and Öztaş (2008). To simplify the data collection, this relation must be defined over a part of the activities of the project. The activities of the deterministic critical path could be considered, or the activities judged by the experts as critical activities. Therefore, it is not necessary to define the relationship for all the activities of the project. For each activity is obtained a number of "very effective" relations and a number of "effective" relations with the risks.

In the step G, the simulation model must be developed. Different computer tools are used to execute the model. The deterministic schedule must be built for project planning software. In addition, the use of spreadsheet program is also necessary. The proposed approach uses MS Project, MS EXCEL and the commercial software @Risk for executing the simulation. With these tools, the proposed mathematical structure for the simulation model could be implemented.

The mathematical structure for the simulation model is defined as follows:

SETS

- N, set of number of risks.
- I, set of risk indexed by i.
- J, set of activities affected by effects of the risks, indexed by j.
- $IME_j \subseteq I$, set of risks i that present a "very effective relation" with the activity j.
- $IE_j \subseteq I$, set of risks i that present an effective relation with the activity j.

DETERMINISTIC PARAMETERS

- $nrve_j$, number of "very effective" relations with the risks i for each activity j.
- nre_j, number of "effective" relations with the risks for each activity j.

- D_j, is the total duration in time units of the activity *j*.
- C_{ij}, parameter which represents the numeric value of the degree of influence of the risk over the activity *j*.

STOCHASTIC INPUT VARIABLES

- E_i, a Bernoulli variable that takes the value of 1 or 0. The value of 1 represents the occurrence of the risk, 0 otherwise. This distribution was chosen due to it could model the nature of the occurrence phenomena of a risk. This variable takes the value depending of the probabilities of occurrence defined in step E.
- IPR_i, a random variable that represents the potential impact of the risk *i*, [time units]. It is described by the probability distribution defined for each risk in step E.

VARIABLES

- DD_j, variable that represents a deterministic duration in time units of the activity *j* (without effect of the risks).
- IRR_j, variable that represents the real impact (in time units) of the risks received by the activity *j*.

MATHEMATICAL CONSTRAINTS

$$C_{ij} = 0.7/nrve_j \; \forall j, i \in IME_j \tag{1}$$

$$C_{ij} = 0.3/nre_j \; \forall j, i \in IE_j \tag{2}$$

$$D_j = DD_j + IRR_j \; \forall j \tag{3}$$

$$D_j = DD_j + \sum_{i}^{N} (E_i \times IPR_i \times C_{ij}) \; \forall j \tag{4}$$

$$RTI_i = \sum_{j} (IPR_i \times C_{ij}) \quad \forall i \tag{5}$$

OUTPUT VARIABLES

- *TDP*, total duration of the project.

The value of the parameter "C_{ij}" is obtained from the qualification of step F. The previously qualitative valuations are converted into a numeric value calculated with the Equations (1) and (2) (proposed Equations based on the CSRAM model, (Ökmen and Öztaş, 2008). As shown in Equation (1), the authors propose 70% as the total influence over the activity of the risks with "very effective" qualifications and the 30% as the total influence over the activity of the risks with "effective" qualifications. The total sum of C_{ij} for each activity must be equal to one, which means that the variations of the activity durations are only explained by the existence of the risks. We calculate the activities duration D_j that are affected by the risks within the simulation by using the Equation (3). Equations (4) detail the calculation of D_j. Also, we have considered the assumption that the variation of the activity durations is only explained by the occurrence of the risks. This is achieved by Equation (3), which defines the duration of an activity as the deterministic duration plus the quantity of added days by the effect of the risks (the real impact of the risks over a specific activity IRR_j). The proposed formula allows considering in the simulation model the potential impact of the risks (IPR_i), the influence of each risks over each activity (C_{ij}), and the occurrence of the risks (E_i). Then, the model should be built, and the simulation properties must be defined (sample size, seed) to run the simulations.

Finally, a tornado diagram is used to measure the influence of each risk in the total duration of the project. This techni que is defined as a diagram in which "input variables that have the highest effect on a selected output variable are shown as horizontal bars at the top of the graph and variables that have a smaller impact are shown at the bottom" (Bodmer, 2014) and could be applied by using the methods proposed in Eschenbach (2006). Therefore a tornado diagram could be used to determine the most important risks. The use of the tornado diagram implies the definition of the input variables. These variables are values of the simulation model that are recorded in each sample, together with the values of the output variable of the model (in this case, the total duration of the project). Subsequently, the input variables are changed dynamically, individually, through a given range of values holding all other input variables at their central value, and recording the lower, the mean, and the upper bound values of the output variable. This process is repeated for each input variable. Later, these results are compared to define which input variable of the tornado diagram has more influence in the output variable of the model. The x-axis of a tornado diagram represents the different values of the result for the output variable. Each bar represents the range of values produced, when each input variable changes (the other variables remaining constant). Finally, the input variables are organized from top to bottom according to the total range produced for the output variable. This variable provides the most extensive range at the top of the diagram. Hence, bars become smaller toward the bottom of the chart, and the overall effect takes on the appearance of a "tornado." To achieve this, we propose the definition of RTI_i, an input variable to the tornado diagram explained in Equation (5).

$$RTI_i = \sum_j (IPR_i \times C_{ij}) \quad \forall i \tag{5}$$

As is shown in Equation (5), the values of RTI_i represents the sum of the impacts (in terms of duration) generated by each risk over the activities j that it affects.

Results and Discussion

Features of the construction project: the construction project is concerned with a medical building for a public university in Colombia. The project owner is the Institution to which the responsibility is assigned for submitting the technical and architectonic requirements, and the execution to the contractor. The contract of the respective project was signed on 28 October 2011; the execution started on 25 November 2011, the deadline was agreed 180 calendar days after the start, meaning until 22 May 2012. The project was delivered 60 calendar days after the deadline on 20 July 2012.

STEP A. RISK IDENTIFICATION

The identification of schedule risks of this work was initially performed by an extensive literature review (Table 1). However, the importance given to these risks is relative to the context where the research projects were performed. Therefore, the most important risks in the papers described in Table 1 are not completely applicable to Colombia, nor to the public university context. Thus, instead of simply choosing one of these studies, a systematic process was developed to extract from these articles the relevant risks for the Colombian and project context (Figure 3).

First, the 471 risks found in the literature review (Table 1) were compared by the authors, to discard repeated risks implicit in others, and the ones not applicable to the real case context. Secondly, two experts of the construction sector were consulted to obtain a practical vision of the risks; with them, some risks were discarded, and others added to the list of risk. In third place, some risks were added from official documents of the university, in which already-identified risks were found. From this process, the risks shown in Table 3 were obtained. Indeed, a list with 55 risks to be evaluated in the qualitative qualification was obtained; each risk referenced by an identifier (ID).

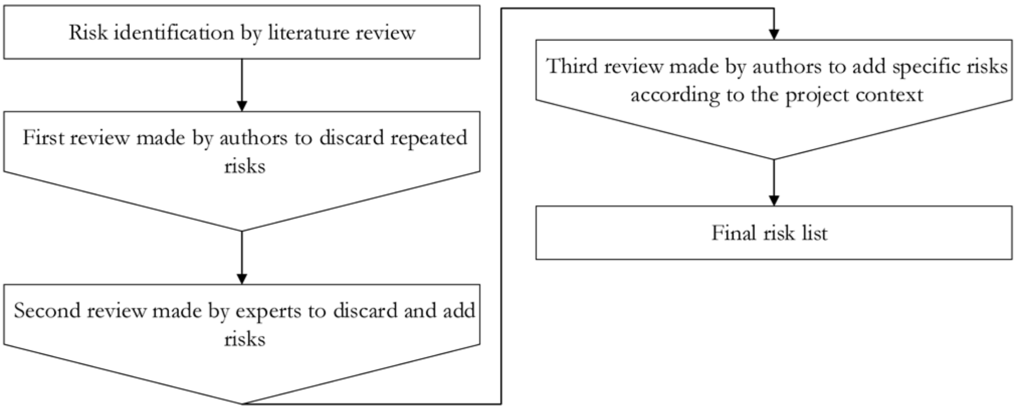

Figure 3 Systematic process to risks identification

STEP B. RISK CATEGORIZATION

When the two experts were consulted about the risks found in Table 3, information about existing risks that affect the success indicators of the construction projects and their possible categorizations was asked. As result of this process, the categories shown in Figure 4 were made. This information was used as support for the next step in the SBSM in which the risks are qualified. Nevertheless, the project owner could use this information to propose risk responses.

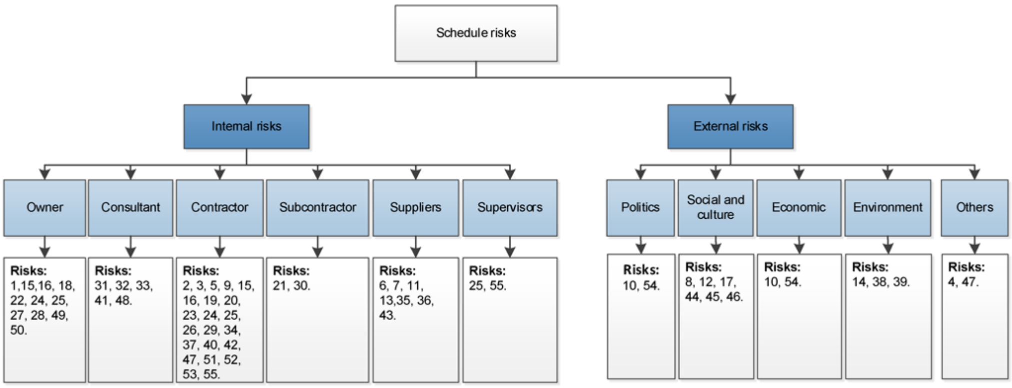

Figure 4 Risks categorization

STEP C. QUALIFICATION OF THE RISK FACTORS

Evaluating by MCS all the risks that affect a construction project is not practical. This is an observation performed by the experts about the revision of existing risk analysis methodologies. For example, it was identified as a long and inaccurate process of asking experts the definition of a matrix relating all project activities and risks. Therefore, in the case of a large project, a qualitative evaluation must be performed, to identify the most important risks, to reduce the number of simulated risks, and thus simplify the quantitative evaluation. For example, if we pretend to model 55 risks that could have been affecting the case study, and their relationship with each of the 128 activities of the project; then 7040 relations must be evaluated (55 times 128). The consulted experts identified this aspect as impractical.

Table 3 Risks identified for the case study

ID	Description	ID	Description
1	Delay in performing inspection and testing by consultant	29	Rain effect on construction activities
2	Late in reviewing and approving design documents by consultant	30	Communication failures between the owner and the contractor
3	Conflicts between consultant and engineers	31	Delays in resolving contractual issues
4	Delays in the work development by inconsistency or lack of clearly of the designs	32	Delays in resolving disputes with the stakeholders
5	Accident during construction	33	Strikes and conflicts of labour
6	Unpredicted technical problems in construction	34	Delays in approvals
7	Lack or departure of qualified staff	35	Delay in performing final inspection and certification by a third party
8	Contractors financial difficulties	36	Delay of material supply by suppliers
9	Defective works and reworks	37	Quality problems of supplier material
10	Delay for construction methods	38	Delay in construction by disorderly conduct
11	Conflicts in sub-contractor's schedule in execution of project	39	Vandalism damage during disturbance of public order.
12	Damage of sorted material while they are needed urgently	40	Thefts to material, equipment and tools Contractor
13	Equipment breakdowns	41	Delays and noncompliance of the subcontractors
14	Misinterpretation of designs	42	Subcontracting changes by their inefficient work
15	Owners delayed payment to contractors	43	Delay in construction by changes to the initial design or lack of definition the relevant areas
16	Delays in obtaining site access and right of way	44	Changes in financing conditions, exchange rates, lending rates, etc.
17	Owners financial difficulties	45	Conflicts between auditors and engineers
18	Slow decision- making by owners	46	Delay in the approval of the auditor in construction progress
19	Conflicts between joint-ownership of the project	47	Flaws in the judgment of the auditor
20	Suspension of work by owner	48	Late delivery of information from consultants

Table 3 continued

ID	Description	ID	Description
21	Changes in material types and specifications during construction	49	Incomplete delivery of information from consultants
22	Delays during construction by user request or relevant areas due to inherent factor in the project	50	Conflicts between consultants and design engineers
23	Inflation and sudden changes in prices	51	Ineffective project planning and scheduling
24	Shortage in material supply and availability	52	Inadequate policies of the contractor
25	Shortage in manpower supply and availability	53	Method of financing and payment to complete the project
26	Shortage in equipment supply and availability	54	Unavailability of services on site
27	Shortage in transport supply and availability	55	Inconsistencies in the sequence and precedence of the schedule that may affect the execution of the project
28	Unforeseen site conditions		

The qualification of the risks could be performed by different techniques, such as the risks probability-impact evaluation, the evaluation of reliability in data, and the evaluation of the importance of risks, among others. The proposed approach, for this step objective, uses the idea of the risks qualification technique "Risk Failure Mode and Effects Analysis" (RFMEA) proposed by Carbone and Tippett (2004), to obtain a first synthesis of the risks to be modelled in the quantitative analysis. RFMEA is a method that implies a qualitative qualification of the risks by a group of experts in three dimensions: the probability of occurrence, the impact and probability of detection, and some steps defined in the technique (Figure 5). In this study, the mentioned technique only was used to qualify, so that only the steps two to six were executed. The RFMEA scheme has been selected to determine the probability, and impact, of detection. Particularly, the RFMEA allows a better way of evaluating the risks that make the project more vulnerable (Carbone and Tippett, 2004).

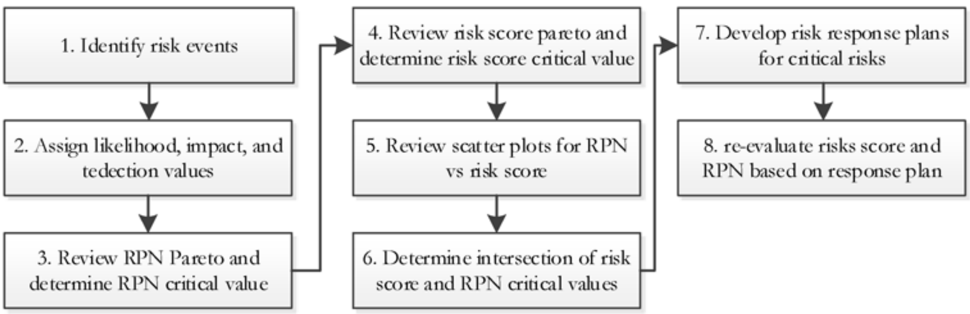

Figure 5 RFMEA steps

First, step two "Assign likelihood, impact and detection values" was executed for the 55 risks, identified above. This is the process in which the risk factors are qualified regarding the probability of occurrence, impact, and detection (values that are assigned through expert consultation). For each estimate, values from 1 to 10 must be defined considering the description and the scales shown in Tables 4, 5, and 6. In the case of the impact value, the RFMEA considers valuations to three dimensions: cost, schedule and technical, but, given the scope of the research, only the schedule scale was used. In the case of detection, the definition of Carbone and Tippett (2004) must be taken: “the ability of detection technique or method(s) to detect the risk event with enough time to plan for a contingency and act upon the risk”.

Table 4 Likelihood values

Value	Likelihood Value Guidelines
9 - 10	Very likely to occur
7 - 8	Will probably occur
5 - 6	Equal chance of occurring or not
3 - 4	Probably will not occur
1 - 2	Very unlikely

Table 5 Impact value guidelines

Value	Schedule
9 - 10	Major milestone impact and > 20% impact to critical path
7 - 8	Major milestone impact and 10% – 20% impact to critical path
5 - 6	Impact of 5% – 10% impact to critical path
3 - 4	Impact of < 5% impact to critical path
1 - 2	Impact insignificant cant

Table 6 The Detection value guidelines

Value	Detection
9 - 10	There is no detection method available or known that will provide an alert with enough time to plan for a contingency.
7 - 8	Detection method is unproven or unreliable; or effectiveness of detection method is unknown to detect in time.
5 - 6	Detection method has medium effectiveness.
3 - 4	Detection method has moderately high effectiveness.
1 - 2	Detection method is highly effective, and it is almost certain that the risk will be detected with adequate time.

Second, steps 3 and 4 (Figure 5) were performed. In this phase, the Risk Score (RS) was calculated as the multiplication of the ratings given in the scales of the Tables 4 and 5, plus the probability and the impact of the risk. Then, the Risk Priority Number (RPN) was obtained as the multiplication of the ratings of each risk in the aspects: probability, impact, plus the detection value (values of Tables 4, 5 and 6). Finally, Pareto diagrams of RS and RPN were constructed so that experts could determine critical values of these indicators. The Pareto distribution diagram is a vertical bar graph useful to analyse the most significant cumulative effect of some variables for a given system. On average, the critical values selected by the experts were 10 and 40 for the RS and the RPN, respectively. The results of this process can be seen in Figure 6. After that, step 5 and 6 of the RFMEA was carried out. This was done, based on the critical values determined in the previous phase. The fifth step is to build a scatter diagram between the RPN and the RS. The objective of stage six, is to find the intersection of the two critical values, to define the critical risks. The result of this phase could be seen in Figure 7. At this stage, note that the worst risk would be that with a high probability of occurrence, high impact on the project, and a low probability of detection (Quadrant I). At the other extreme, the least significant risk would be one that has a low probability of occurrence, low impact, and a high probability of detection (Quadrant III).

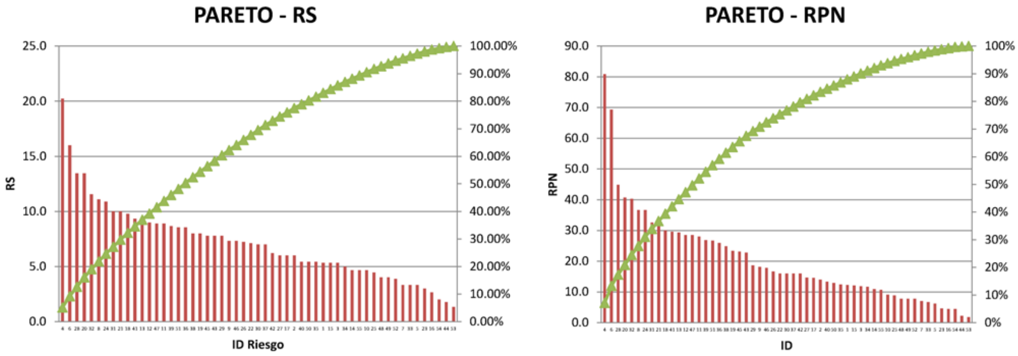

Figure 6 Pareto diagrams

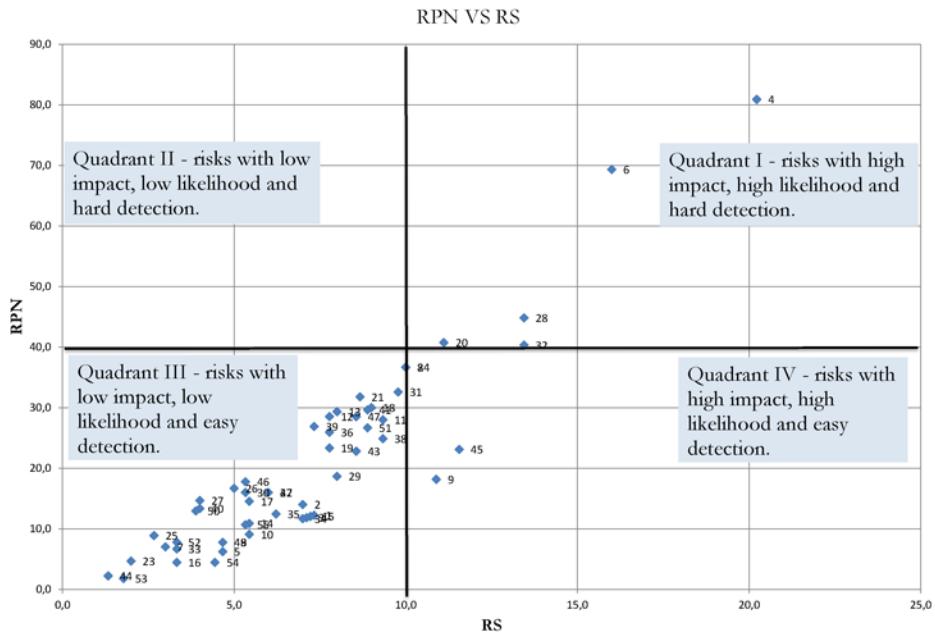

Figure 7 Risks scatter plot

From this process, the definitive list of risks to evaluate, in the qualitative analysis of risks, was obtained (Table 7). These are the risks, located in Quadrant I of Figure 7, that correspond to the RFMEA performed with the average ratings of the experts (risks 4, 6, 28, 20 and 32). Also, the added risks when applying the RFMEA on an individual basis to each expert (risks 8, 29, 41, 18 and 31).

STEP D. DETERMINISTIC SCHEDULE DEVELOPMENT

The activities, relations and project durations were taken from the physical schedule presented by the contractor. In this document, the deterministic program was elaborated by using Microsoft Project software (CPM method). The project had 144 activities with precedence constraints.

Table 7 Risks to be simulated

ID	Description
4	Delays in the work development by inconsistency or lack of clearly of the designs
6	Unpredicted technical problems in construction
28	Unforeseen site conditions
20	Suspension of work by owner
32	Delays in resolving disputes with the stakeholders
8	Contractors financial difficulties
29	Rain effect on construction activities
41	Delays and noncompliance of the subcontractors
18	Slow decision- making by owners
31	Delays in resolving contractual issues

STEP E. DEFINITION OF THE PROBABILITY AND POTENTIAL IMPACT OF THE IDENTIFIED RISKS

The probability of occurrence of each risk was defined by using criteria of experts. The parameters of minimum, expected, and maximum values of duration of the potential impact were determined for each risk (Table 8).

Table 8 Risks, occurrence probability and triangular distribution parameters of the potential impact

ID	Occurrence probability	Minimum potential impact (days)	Expected potential impact (days)	Maximum potential impact (days)
4	70%	15	30	90
6	40%	15	20	60
28	15%	5	10	15
20	50%	15	30	60
32	20%	30	45	60
8	10%	5	10	15
29	5%	10	15	20
41	5%	10	15	20
18	70%	15	30	90
31	30%	15	30	90

STEP F. DEFINITION OF INFLUENCE DEGREES OF RISKS ON THE ACTIVITIES

The influence degrees of risks on activities were defined (Table 9). The experts defined the qualitative description to the relations between risks and the project activities they considered as critical. This was done using the values effective (*e*) or very effective (*ve*).

Table 9 Influence degrees of risks on the activities in terms of effective (*e*) or very effective (*ve*)

	Risks *i* (ID)											
Activity	4	6	28	20	32	8	29	41	18	31	$nrve_j$	nre_j
1.8		e	ve				ve				2	1
2.6	ve	e				e	e				1	3
2.7				ve	ve					e	2	1
6.1	ve								e		1	1
8.3	ve	ve		ve	e	ve	e		ve	ve	6	2
9.2	ve	ve		e							2	1
11.3	ve	ve		e	e	e		ve	e	e	3	5
12.3								ve	e		1	1
12.7								ve	e		1	1

STEP G. MODELLING OF THE DELAY-RISK IMPACTS ON THE SCHEDULE

The proposed model was elaborated on a spreadsheet of Microsoft Excel 2013 and the simulation software used was @Risk. This software supports integration between the MCS and MS Project, allowing the construction of a project schedule with the CPM methodology for each simulated scenario. The input variables of the model were defined as the occurrences of risks and the potential impacts. Thus, a Bernoulli distribution was assigned to every risk with the probabilities obtained in step E. Moreover, the distributions for the potential impacts of every risk were defined as triangular distribution using the parameters of minimum, expected, and maximum potential impact. Subsequently, the C_{ij} parameter which models the degree of influence of the risk *i* over the activity *j*, was calculated using equation (1) and (2), the values are shown in Table 10. Then the necessary spreadsheet formulas were defined to implement equation (4) to define the duration of the activities affected by the risks. After this, the total duration of the project was selected as output variable of the simulation model.

Table 10 C_{ij}, numeric value of the degree of influence of the risk *i* over the activity *j*

	Risks *i* (ID)									
Activity *j*	4	6	28	20	32	8	29	41	18	31
1.8		0.30	0.35				0.35			
2.6	0.70	0.10				0.10	0.10			
2.7				0.35	0.35					0.30
6.1	0.70								0.30	
8.3	0.12	0.12		0.12	0.15	0.12	0.15		0.12	0.12
9.2	0.35	0.35		0.3						
11.3	0.23	0.23		0.06	0.06	0.06		0.23	0.06	0.06
12.3								0.70	0.30	
12.7								0.70	0.30	

Finally, the inputs for the tornado diagram were registered. The values of RTI_i were used as an input parameter for the tornado diagram, as is defined in the equation (5).

SIMULATION RESULTS

The results of the simulation of the SBSM applied to the case study were: the descriptive statistics of three experiments. For each experiment a simulated sample of the total duration of the project was calculated; a statistical distribution of the total duration of the project and a quantitative measurement of the variability caused by each risk in the total execution time of the project. The descriptive statistics allow seeing the consistency of the results when the series of random numbers are changed, the statistical distribution was estimated as a project completion date associated with a confidence level and the variability generated in the duration of the project.

The results of the simulation process are independent of the series of random numbers generated. Three experiments were performed to calculate the descriptive statistics of the total duration of the project, each one with a sample of 1000 simulations and with a different seed for the random values. The results obtained for different seeds are either independent (ideal main goal) or have a high probability of being nearly independent. These results are listed in Table 11. Note that the values of the mode are equal, and both the average and median can be approximated to 190 and 189 days, respectively. Regarding the variation indicators, there are slight variations in the maximum duration but in general, the results of each experiment show the same behaviour. Therefore, it can be affirmed that the results are not affected by the series of random numbers used.

Table 11 Statistical results of the simulations

Statistical	Experiment 1	Experiment 2	Experiment 3
Minimum	157.00	157.00	157.00
Maximum	237.85	241.00	254.62
Average	189.55	189.82	189.64
Mode	157.00	157.00	157.00
Median	188.40	189.46	188.77
Est. Dev.	17.42	18.00	18.01
Kurtosis	2.45	2.38	2.59

Figure 8 shows the probability distribution of the duration of the project completion for Experiment 1. The distribution presents a flared behaviour that does not exceed 7% of any histogram value. Note that, if any value from the range of possibilities is chosen (157 to 238 days) as the predicted duration of the project, then it could be defined a probability (cumulative probability) of completing the project in less or equal time than the selected duration. This fact makes it possible to predict the total duration of the project based on percentiles, which can create a level of confidence in estimating the duration of the project.

The percentiles of the distribution of the first experiment are shown in Table 12. This table shows the range of possibilities that could be chosen, for example, at 5% reliability for the complete project on June 1- 2012, and a reliability level of 99% for August 20 of the same period. With this information, the project professionals were able to choose the project completion forecast on a quantitative basis; a clear advantage of the MCS.

However, it is necessary to validate the inferences of the model proposed in the SBSM. This is because the mathematical way of modelling risks and their interaction with activities differs

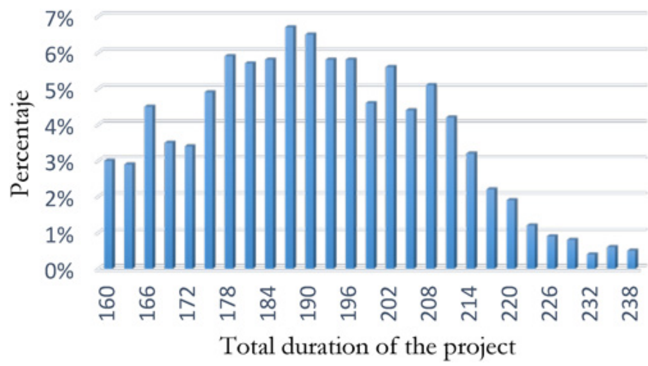

Figure 8 Probability distribution of the duration of the project completion, experiment 1

between different MCS models. Also, the mathematical formulation used, together with the quality of the input data, is what ultimately determines the cost of constructing the model, and its level of precision. The prediction error associated with each level of confidence of the SBSM was calculated. The relative difference between the date associated with each percentile and the actual date of completion of the project was precisely calculated (Table 12).

Table 12 Forecast based on reliability of the duration of the project completion

Real project duration - 205 days - 07/20/2012							
Percentile	Error	Forecast		Percentile	Error	Forecast	
		days	date			days	date
5%	-20.6%	162	06/01/2012	55%	-6.4%	191	07/04/2012
10%	-18.6%	166	06/05/2012	60%	-4.9%	194	07/09/2012
15%	-16.7%	170	06/11/2012	65%	-3.9%	196	07/11/2012
20%	-14.7%	174	06/14/2012	70%	-2.5%	199	07/14/2012
25%	-13.7%	176	06/18/2012	75%	-1.0%	202	07/18/2012
30%	-12.3%	179	06/21/2012	80%	1.0%	206	07/21/2012
35%	-10.8%	182	06/23/2012	85%	2.5%	209	07/25/2012
40%	-9.8%	184	06/27/2012	90%	3.9%	212	07/30/2012
45%	-8.8%	186	06/29/2012	95%	6.9%	218	08/06/2012
50%	-7.8%	188	07/02/2012	99%	13.7%	232	08/20/2012

The results of Table 4 show good projection behaviour since the actual termination date is within the range of possibilities. However, we consider positive errors from 80% to 99% levels of confidence. This behaviour does not imply that with higher confidence intervals, the results of the proposed approach become less reliable. On the contrary, this is explained because in any case the prediction is an upper limit for the possible value of the duration of the project, so in the last percentiles it is very likely to find an overestimation of the time necessary to execute the project. However, if any of the common confidence levels in statistics such as 90%, 95% and 99% are used (Lawsky et al., 2014), the errors of 3.9%, 6.9% and 13.7% respectively, continue being smaller than those of the deterministic programming method (Table 13). In addition, the errors are positive so that in any case they would have avoided the breach of the contract and the fines derived from it.

Table 13 Forecast compared against the actual performance of the project

	CPM	Stochastic (90%)	Agreed in the contract
Date	05/25/2012	07/30/2012	05/22/2012
Duration	157	213	154
Error	23,41%	3,90%	24,88%

Then, the following results were compared: the deadline, determined by the professionals through the simulation model, for a reliability level of 90% (30 July 2012); the date given by the deterministic CPM model (25 May 2012); the contracted agreement (22 May 2012); and the date when the project was really finished (the work started on 25 November 2011 and ended on 20 July 2012). The comparison was performed with regard to working days associated with each of the deadlines proposed by the two models, and the date agreed upon in the contract. The error of each model is obtained as the relative difference (in working days) of the promised dates versus the real ending date, and the real duration of the project corresponding to 204 working days (Table 13). This comparison indicates that the deadline forecast of the proposed SBSM with a reliability level of 90% presented an error of 3.9%, compared to the real duration of the project. Moreover, the CPM model and the contractual deadline presented errors of 23.4% and 24.8%, respectively. These results confirm that the proposed model is notable. Also, the simulation results suggest that the project completion date agreed in the contract has a zero probability of compliance. This fact means that, if conditions of uncertainty are considered, the deadline agreed on the contract is impossible to achieve.

Furthermore, a quantitative measure of the impact of each risk on the total duration of the project by a tornado diagram was performed (Figure 9). This tool defines higher variability generators on the deadline of the project as the risks: delays in work development by inconsistency or lack of clarity in designs; slow decision- making by owners; and unpredicted technical problems in construction.

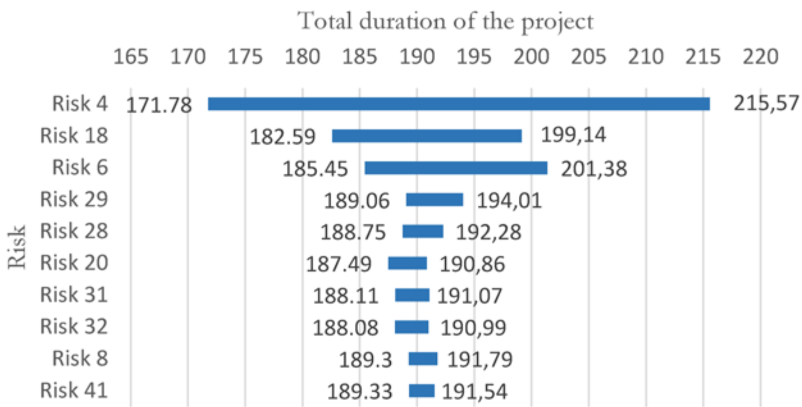

Figure 9 Tornado diagram of the schedule risks, simulation 1

Two further experiments were performed to ensure a different random seed to verify the stability of the risk rank previously described. This allowed a validation of the obtained results about the risks that most affect the entire duration of the project (Table 14). The results show that the three first risks have been at the top while the other risks may vary in importance. The behaviour of the risks in a position greater than four is explained because the impact that they generate in the duration of the project does not differ significantly. Besides, the most important risk selection is stable, since the first three risks of the first simulation were also the first three risks for the additional experiments. This result implies that series of random numbers do not affect the risk ranking. Nevertheless, this result is subject to the case study and cannot be generalized to all construction projects. However, the SBMM can be replicated for any other project provided that the risks analysed are redefined for the environment that is to be studied.

Table 14 Importance rank of the simulated risks

Position	Simulation 1 (ID)	Simulation2 (ID)	Simulation3 (ID)
1	4	4	4
2	18	6	18
3	6	18	6
4	29	28	20
5	28	20	29
6	20	31	32
7	31	32	28
8	32	29	31
9	8	41	41
10	41	8	8

Conclusion

In this paper a practical and useful simulation-based methodology to assess risks causing delays in the schedule of construction projects is proposed. The proposed approach was constructed by a method based on an exhaustive review of the literature and including the participation of experts in its design. Additionally, a novel mathematical formulation was included in the methodology, for an MCS model that represents the occurrence of the risks and the way in which they impact the activities of the project. Then, the proposed approach was applied to a real case of an already-constructed project of a medical building of a public university in Colombia. From this exercise, a forecast of the date of completion of the work and a quantitative assessment of the risks was evaluated. The comparison of the obtained results against the historical records of the case study, shows that the proposed methodology works appropriately, and produces realistic results to achieve a minimum error in the total duration estimation of the Project. It was found, when regarding the risks prioritization, that the proposed structure enriches the impact analysis of the risks. These results, together with the opinion of experts from the construction sector, prove that the methodology is effective when using resources available to planners of construction projects in an emerging country such as Colombia. The proposed approach could be extended as a general method of risk analysis of construction projects based on MCS. Indeed, the proposed approach could be applied to another environment by identifying the appropriate risks.

The literature review delivered two conclusions. The first one is that the identification of the risks of a construction project must be performed from its environment. This is because the results of the review show that the risks vary according to the geographical context in which the project is carried out. For example, the extremely hot weather was found to be a risk of delay; however, this does not apply in countries in South America. Additionally, not only does it affect the country or region, but it also found that the type of project and the type of institution where it is carried out have an impact. In fact, it was necessary for the case study to adjust the list of risks for the institution that owns the project. It highlights then the results and experiences of this research, that for each project the risks must be carefully determined. However, in the literature there are risk surveys that can be taken as a reference to streamline this process. In this sense, this paper contributes to the literature of the considered problem.

The second conclusion derived from the review, is that the methodology proposed in this paper uses an MCS model with a new mathematical formulation, to represent the effect of the risks of delay in the duration of the schedule. This was ensured first, by establishing several risk analysis methods as a design reference, and secondly, by analysing the methods together with experts from the construction sector, with the restriction that the model to be proposed should be applicable with little reference information. This was a characteristic of the working environment of the case study. Because of this process, the proposed model is formulated. This is based on the definition of a stochastic variable defined as the "impact of risk", a random variable of occurrence of a risk and a correlation matrix of risks-activities. All these elements can be defined from the judgment of experts or based on distribution adjustments, according to the availability of information. Also, all the elements were defined in such a way that the effort of the programmer was concrete, but that it would provide the possibility of obtaining a comprehensive, accurate and objective schedule risk analysis model. For all these reasons, the model proposed in this paper establishes a new scheme, to represent the effect of the risks of delay in the duration of a construction project and which, as already mentioned above, proved its functionality in the case study.

Other conclusions are derived from the application of the methodology proposed for the case study. This is based on the comparison of the results of the simulation against the real history of the project. It is evident, that the proposed approach is a better predictor than the CPM of the total time of completion. Furthermore, the comparison of the prioritization of risks with the real history of the project shows that all the predicted risk could affect the duration of the project. On the other hand, although the application was based on data from a constructive project in Colombia, the methodology was designed for elements that are common to all construction projects. Additionally, the project's environment only changes the risks to which the project is exposed, so by simply re-defining the base risks of the methodology, it is possible to apply the proposed method in another context. For all the above, it is evident that the methodology could: i) improve the estimation of the duration of a construction project against the critical route method, ii) enrich the analysis of the construction project schedule by providing a prioritization of risks that can be used to focus risk management decisions (e.g. mitigation, elimination, among others) on the most important risks, and iii) be the basis of a risk management model for construction projects.

Nevertheless, future research could be directed to consider aspects such as the natural variation of the activities duration, other project objectives such as costs or quality, the use of different scheduling techniques as a basis rather than CPM, consider the scheduling process resource constraints, and consideration of the addition of activities when adverse events occur. Another interesting study is to measure the level of applicability of different techniques to the one proposed in this paper and others risk analysis methods.

Acknowledgments

The authors would like to express their gratitude to the anonymous referees for their valuable comments, which helped to improve the paper significantly.

References

Ahmed, S.M., Ahmad, R., Saram, D.E. and Darshi, D., 1999. Risk management trends in the Hong Kong construction industry: a comparison of contractors and owners' perceptions. *Engineering construction and Architectural management*, [e-journal] 6(3), 225-234. https://doi.org/10.1108/eb021114

Ahuja, H.N. and Nandakumar, V., 1985. Simulation model to forecast project completion time. *Journal of Construction Engineering and Management*, [e-journal] 111(4), 325-342. https://doi.org/10.1061/(ASCE)0733-9364(1985)111:4(325)

Andi., 2006. The importance and allocation of risks in Indonesian construction projects. *Construction Management and Economics*, 24(1), pp.69-80. https://doi.org/10.1080/01446190500310338

Antill, J.M. and Woodhead, R.W., 1990. *Critical path methods in construction practice*. New York: John Wiley & Sons.

Assaf, S.A. and Al-Hejji, S., 2006. Causes of delay in large construction projects. *International Journal of Project Management*, [e-journal] 24(4), pp.349-57. https://doi.org/10.1016/j.ijproman.2005.11.010

Aziz, R.F., 2013. Ranking of delay factors in construction projects after Egyptian revolution. *Alexandria Engineering Journal*, [e-journal] 52(3), pp.387-406. https://doi.org/10.1016/j.aej.2013.03.002

Bodmer, E. 2014. Corporate and project finance modeling: Theory and practice. Hoboken, New Jersey: John Wiley & Sons.

Bowman, R.A., 2007. Efficient sensitivity analysis of PERT network performance measures to significant changes in activity time parameters. *Journal of the Operational Research Society*, [e-journal] 58(10), pp.1354-60. https://doi.org/10.1057/palgrave.jors.2602297

Brucker, P., Drexl, A., Möhring, R., Neumann, K. and Pesch, E., 1999. Resource-constrained project scheduling: Notation, classification, models, and methods. *European Journal of Operational Research*, [e-journal] 112(1), pp.3-41. https://doi.org/10.1016/S0377-2217(98)00204-5

Carbone, T.A. and Tippett, D.D., 2004. Project risk management using the project risk FMEA. *Engineering Management Journal*, [e-journal] 16(4), pp.28-35. https://doi.org/10.1080/10429247.2004.11415263

Carr, R.I., 1979. Simulation of construction project duration. *Journal of the Construction Division*, 105(2), pp.117-28.

Chan, D.W. and Kumaraswamy, M.M., 1997. A comparative study of causes of time overruns in Hong Kong construction projects. *International Journal of Project Management*, [e-journal] 15(1), pp.55-63. https://doi.org/10.1016/S0263-7863(96)00039-7

Chan, A.P.C. and Chan, A.P.L., 2004. Key performance indicators for measuring construction success. *Benchmarking: an international journal*, *11*(2), 203-221. https://doi.org/10.1108/14635770410532624

Choudhry, R.M., Aslam, M.A., Hinze, J.W. and Arain, F.M. 2014. Cost and schedule risk analysis of bridge construction in Pakistan: Establishing risk guidelines. *Journal of Construction Engineering and Management*, [e-journal] 140(7), 04014020. https://doi.org/10.1061/(asce)co.1943-7862.0000857

Dey, P.K., 2010. Managing project risk using combined analytic hierarchy process and risk map. *Applied Soft Computing*, [e-journal] 10(4), pp.990-1000. https://doi.org/10.1016/j.asoc.2010.03.010

Dikmen, I., Birgönül, M.T. and Arikan, A.E., 2004. A critical review of risk management support tools. *Proceedings, ARCOM 2004, Association of Researchers in Construction Management*, Heriot Watt University, U.K., 2, pp.1145-54.

Dikmen, I., Birgonul, M.T., Tah, J.H. and Ozer, A.H, 2012. Web-Based Risk Assessment Tool Using Integrated Duration–Cost Influence Network Model. *Journal of Construction Engineering and Management*, [e-journal] 138(9), pp.1023-34. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000547

El-Sayegh, S.M., 2008. Risk assessment and allocation in the UAE construction industry. *International Journal of Project Management*, [e-journal] 26(4), pp.431-38. https://doi.org/10.1016/j.ijproman.2007.07.004

Eschenbach, T.G., 2006. Constructing tornado diagrams with spreadsheets. [e-journal] *The Engineering Economist*, 51(2), pp.195-204. https://doi.org/10.1080/00137910600695676

Flanagan, R. and Norman, G., 1993. *Risk Management and Construction*. Oxford: Blackwell Scientific.

Galway, L., 2004. Quantitative Risk Analysis for Project Management. Santa Monica, CA: RAND Corporation, http://sbir. nasa. gov/SBIR/successes/ss/10-018text. html.

Hartmann, S. and Briskorn, D., 2010. A survey of variants and extensions of the resource-constrained project scheduling problem. *European Journal of Operational Research*, [e-journal] 207(1), pp.1-14. https://doi.org/10.1016/j.ejor.2009.11.005

Herroelen, W., De Reyck, B. and Demeulemeester, E., 1998. Resource-constrained project scheduling: a survey of recent developments. *Computers & Operations Research*, [e-journal] 25(4), pp.279-302. https://doi.org/10.1016/S0305-0548(97)00055-5

Icmeli, O., Selcuk Erenguc, S. and Zappe, C. J., 1993. Project scheduling problems: a survey. *International Journal of Operations & Production Management*, [e-journal] 13(11), pp.80-91. https://doi.org/10.1108/01443579310046454

Jun, D.H. and El-Rayes, K., 2011. Fast and accurate risk evaluation for scheduling large-scale construction projects. *Journal of Computing in Civil Engineering*, [e-journal] 25(5), pp.407-17. https://doi.org/10.1061/(asce)cp.1943-5487.0000106

Kangari, R., 1995. Risk management perceptions and trends of US construction. *Journal of Construction Engineering and Management*, [e-journal] 121(4), pp.422-29. https://doi.org/10.1061/(ASCE)0733-9364(1995)121:4(422)Kartam, N.A. and Kartam, S.A., 2001. Risk and its management in the Kuwaiti construction industry: a contractors' perspective. *International Journal of Project Management*, [e-journal] 19(6), pp.325-35. https://doi.org/10.1016/S0263-7863(00)00014-4

Kolisch, R. and Hartmann, S, 2006. Experimental investigation of heuristics for resource-constrained project scheduling: An update. *European Journal of Operational Research*, [e-journal] 174(1), pp.23-37. https://doi.org/10.1016/j.ejor.2005.01.065

Kolisch, R. and Padman, R., 2001. An integrated survey of deterministic project scheduling. *Omega*, [e-journal] 29(3), pp.249-72. https://doi.org/10.1016/S0305-0483(00)00046-3

Kwak, Y.H. and Ingall, L., 2007. Exploring Monte Carlo simulation applications for project management. *Risk Management*, [e-journal] 9(1), pp.44-57. https://doi.org/10.1057/palgrave.rm.8250017

Lawsky, E., Ottman, L., Almukkahal, R., Meery, B. and DeLancey, D., 2014. *CK-12 Advanced Probability and Statistics*. 2nd ed. Flexbook, p.243.

Levitt, R.E. and Kunz, J.C., 1985. Using knowledge of construction and project management for automated schedule updating. *Project Management Journal*, 16(5), pp.57-76.

Ling, F.Y.Y. and Hoi, L., 2006. Risks faced by Singapore firms when undertaking construction projects in India. *International Journal of Project Management*, [e-journal] 24(3), pp.261-70. https://doi.org/10.1016/j.ijproman.2005.11.003

Luu, T. T. G., Sthiannopkao, S., and Kim, K. W., 2009. Arsenic and other trace elements contamination in groundwater and a risk assessment study for the residents in the Kandal Province of Cambodia. *Environment International*, 35(3), pp. 455-460. https://doi.org/10.1016/j.envint.2008.07.013

Nasirzadeh, F., Khanzadi, M. and Rezaie, M., 2014. Dynamic modeling of the quantitative risk allocation in construction projects. *International Journal of Project Management*, [e-journal] 32(3), pp.442-51. https://doi.org/10.1016/j.ijproman.2013.06.002.

Nordmeyer, B., 2018. What Are the Pros & Cons of PERT Charts? [online] Available at: Small Business - Chron.com, http://smallbusiness.chron.com/pros-cons-pert-charts-42359.html. [Accessed 19 May 2018].

Odeh, A.M. and Battaineh, H.T., 2002. Causes of construction delay: traditional contracts. *International Journal of Project Management*, [e-journal] 20(1), pp.67-73. https://doi.org/10.1016/S0263-7863(00)00037-5

Ökmen, Ö. and Öztaş, A., 2008. Construction project network evaluation with correlated schedule risk analysis model. *Journal of Construction Engineering and Management*, [e-journal] 134(1), pp.49-63. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:1(49)

Özdamar, L. and Ulusoy, G., 1995. A survey on the resource-constrained project scheduling problem. *IIE transactions*, [e-journal] 27(5), pp.574-86. https://doi.org/10.1080/07408179508936773

Öztaş, A. and Ökmen, Ö., 2004. Risk analysis in fixed-price design–build construction projects. *Building and environment*, [e-journal] 39(2), pp.229-37. https://doi.org/10.1016/j.buildenv.2003.08.018

Öztaş, A. and Ökmen, Ö., 2005. Judgmental risk analysis process development in construction projects. *Building and Environment*, [e-journal] 40(9), pp.1244-54. https://doi.org/10.1016/j.buildenv.2004.10.013

PMI, 2013. A guide to the project management body of knowledge (PMBOK®). Fifth Edition. Project Management Institute.

Poh, Y.P. and Tah, J.H.M., 2006. Integrated duration–cost influence network for modelling risk impacts on construction tasks. *Construction Management and Economics*, [e-journal] 24(8), pp.861-68. https://doi.org/10.1080/01446190600658891

Ranasinghe, M. and Russell, A.D., 1992. Treatment of correlation for risk analysis of engineering projects. *Civil Engineering Systems*, [e-journal] 9(1), pp.17-39. https://doi.org/10.1080/02630259208970637

Tysiak, W., 2011. Risk management in projects: the Monte Carlo approach versus PERT. In: IEEE (Institute of Electrical and Electronics Engineers) *6th IEEE International Conference, Intelligent Data Acquisition and Advanced Computing Systems (IDAACS): Technology and Applications*. Prague, Czech Republic, 15-17 September 2011, 2, pp.906-10. https://doi.org/10.1109/idaacs.2011.6072904

Touran, A. and Wiser, E.P., 1992. Monte Carlo technique with correlated random variables. *Journal of Construction Engineering and Management*, [e-journal] 118(2), pp.258-72. https://doi.org/10.1061/(ASCE)0733-9364(1992)118:2(258)

Uzzafer, M., 2010. A New Dimension in Software Risk Managment. *World Academy of Science, Engineering & Technology*, [e-journal] 64, pp.340-44.

Vanhoucke, M., 2012. Measuring the efficiency of project control using fictitious and empirical project data. *International Journal of Project Management*, [e-journal] 30(2), pp.252-63. https://doi.org/10.1016/j.ijproman.2011.05.006

Waledzik, K., and Mandziuk, J., 2017. (in press corrected proof). Applying Hybrid Monte Carlo Tree Search Methods to Risk-Aware Project Scheduling Problem. *Information Sciences*. https://doi.org/10.1016/j.ins.2017.08.049

Wallace, I., 2010. *Schedule risk and contingency using @RISK and probabilistic analysis*. Ithaca, NY: Palisade Corporation.

Wang, S.Q., Dulaimi, M.F. and Aguria, M.Y., 2004. Risk management framework for construction projects in developing countries. *Construction Management and Economics*, [e-journal] 22(3), pp.237-52. https://doi.org/10.1080/0144619032000124689

Wang, W.C. and Demsetz, L.A., 2000. Model for evaluating networks under correlated uncertainty-NETCOR. *Journal of Construction Engineering and Management*, [e-journal] 126(6), pp.458-66. https://doi.org/10.1061/(ASCE)0733-9364(2000)126:6(458)

Wang, C., Hong, J., Kafouros, M., and Wright, M., 2012. Exploring the role of government involvement in outward FDI from emerging economies. *Journal of International Business Studies*, 43(7), pp. 655-676. https://doi.org/10.1057/jibs.2012.18

Woolery, J.C. and Crandall, K.C., 1983. Stochastic network model for planning scheduling. *Journal of Construction Engineering and Management*, [e-journal] 109(3), pp.342-54. https://doi.org/10.1061/(ASCE)0733-9364(1983)109:3(342)

Yuan, H., 2017. Barriers and countermeasures for managing construction and demolition waste: A case of Shenzhen in China. *Journal of Cleaner Production*, 157, pp. 84-93. https://doi.org/10.1016/j.jclepro.2017.04.137

Zafra-Cabeza, A., Ridao, M.A. and Camacho, E.F., 2004. An algorithm for optimal scheduling and risk assessment of projects. *Control Engineering Practice*, 12(10), pp.1329-38. https://doi.org/10.1016/j.conengprac.2004.03.016

Zhang, Z. and Chu, X., 2011. Risk prioritization in failure mode and effects analysis under uncertainty. *Expert Systems with Applications*, [e-journal] 38(1), pp.206-14. https://doi.org/10.1016/j.eswa.2010.06.046

Zhi, H., 1995. Risk management for overseas construction projects. *International Journal of Project Management*, [e-journal] 13(4), pp.231-37. https://doi.org/10.1016/0263-7863(95)00015-I

Zhong, D. H., Liu, K. J., and Yang, X. G., 2005. Uncertainty Analysis for Construction Scheduling with Flexible Network Simulation. *Systems Engineering-theory & Practice*, 2, pp. 17.

Zhong, D., Yang, S., Chang, H., Yu, J. and Yan, F., 2015. Construction schedule risk analysis of high roller-compacted concrete dams based on improved CSRAM. *Science China Technological Sciences*, [e-journal] 58(6), pp.1021-30. https://doi.org/10.1007/s11431-015-5781-8

Zhong, D., Bi, L., Yu, J. and Zhao, M., 2016. Robustness analysis of underground powerhouse construction simulation based on Markov Chain Monte Carlo method. [e-journal] *Science China Technological Sciences*, 59(2), pp.252-64. https://doi.org/10.1007/s11431-015-5859-3