A Methodological Proposal for Risk Analysis in the Construction of Tunnels

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Abstract

Colombia is in the process of modernizing and changing its road infrastructure and, despite the fact that in this process the government entities request the contractors elements of risk analysis and assessment, this country has a precarious risk management for infrastructure projects. This research is intended to determine the project schedule affectation due to the materialization of risks and to stablish a risk assessment methodology considering the context of the project. The proposed methodology first takes into account the quantification of the probability of occurrence of the event or risk with the Bayesian analysis and their respective networks, in order to look at the interaction of their causes and their repercussion in the final event analyzed. Subsequently, the impact of the risk on the duration of the activity is found. Finally, the risk value (P $\times$ I) is calculated using a Monte Carlo Simulation technique, obtaining as a result a value in days of possible delay that must be compared with the value that details the initial programming. The methodology is realistic since it considers any type of risk that could be presented in a project, from engineering problems, to social events. Currently, the methodology is being implemented in a real project in order to evaluate it against the progress of the same, obtaining information so that later, organizations can propose the necessary contingency measures to deal with the risks presented.

Keywords

Risk analysis • Bayesian analysis • Monte Carlo simulation • Forecast value • Project scheduling • Underground excavation

98.1 Introduction

Road infrastructure is one of the main index for competitiveness in a country, thus, having in mind the competitiveness increase, Colombia is under a huge process to renew its roads, called fourth generation (4G) roads. The construction of new roads, bridges, and tunnels among other structures, highlights the need to set conditions that guarantee the quality, the cost, the execution time and the scope stablished. In Colombia, risk management related to infrastructure projects has been ignored by companies working with road infrastructure. In the 4G routes contracts, in which construction of tunnels is their base component, analysis and risk assessment are represented by a matrix. These requirements demanded by the government to the contractors show that there is an institutional effort to develop risk management in projects. Nonetheless, this effort remains insufficient to develop a complete quantification, subsequent implementation and monitoring. Matrix analyses based on qualitative data generate a bias since different interpretations can arise from the risk assessment.

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I. Mutis and T. Hartmann (eds.), *Advances in Informatics and Computing in Civil and Construction Engineering*,
https://doi.org/10.1007/978-3-030-00220-6_98

In the Colombian productive environment, the execution of engineering projects related with soil removal link with infrastructure, show that it exists a handicap in the planning, execution and monitoring of the activities that haven't had a correct schedule control. This fact is related to the process of recognition and assessment of risks in the construction tasks. This research is intended to determine, in percentage, how much will be affected the construction schedule of a project by the contractual milestones when introducing risk assessment in comparison with the initial one, which is the best method to assess the risk considering the context that involves the contractual situation for companies that work with public or private entities, and if the presented methodology effective to identify and quantify the risks that surround the subterranean terrain removal.

98.2 The State of the Art of Risk Management in Infrastructure Projects

Different methodologies of risk assessment have been published all around the world, a lot of them related to underground excavation and tunneling. Models can describe, with a great precision, the uncertainty that comes with the prediction of geotechnical conditions and the variations in the performance rate and unitary costs. Nevertheless, these models do not consider other factors such as unexpected events or social and organizational conditions related to local context, which can increase in a substantial way the uncertainty, the costs and the time length of the project. To build a realistic model, these factors must be considered.

Castillo [1] stablishes that the Bayesian analysis is related with a probability assignment to an event, or the probability distribution assignment to a random variable. This variable represents a relevant characteristic in the decision making that, in this research, corresponds to the causal relationship between previous events and risk probability. Bayesian analysis has been an effective tool to support the decision-making. Špačková and Straub [2], illustrate the implementation of Bayesian networks in tunneling processes.

Einstein and Souza [3], describe a technique that addresses to the geotechnical problems by specifying its risk, developing first a methodology that allows to identify the main risk origins in the geotechnical field in the specific context of a project. Then, a quantitative risk analysis must be done to identify the best construction strategies considering the best option the one with a minimum risk. Nowadays, there is no information to upgrade the exactitude of time length estimations in tunnel constructions. This information would be a useful tool to learn systematically from past experiences. Without the required information, this problem present in projects must be solved by the estimation from an expert in the field. Risk analysts must support their job with data bases containing information that improves the uncertainty quantification.

According to ISO 31000: 2011 [4], Risk Management is defined as the "*Systematic application of policies, procedures and management practices to the activities of communication, consultation, establishment of context, and identification, analysis, evaluation, treatment, monitoring and risk review*". The Impact "*is the consequence of the materialization of an event on the different objectives of the project*". The impact can then be measured in terms: monetary, time periods, injuries, deaths, environmental damage, and organizational reputation, among others. Risk in tunnel engineering refers to the adverse influence of events that occur during construction. Its effects may include economic loss, construction delays, casualties, environmental damage (to the natural environment, as well as the surrounding infrastructure), and social problems (including policy and safety impacts) [5]. To reduce the uncertainty during the construction of the project, the dynamic and systematic control of risks is applied in different phases of the life cycle within a project. Dynamic risk management is aimed at all stages of the project, from approval to completion. Effective control is based on dynamic feedback and real-time control [6]. This management also explains why risk efficiency is a key aspect of good project management practices, which provides a basis for future risk mitigation methods.

Bayesian statistics have formulated a coherent statistical theory that has allowed structuring and modeling subjective Probability in the context of a decision problem. This probability is understood as "*the degree of belief that an individual (an expert, a panel or interdisciplinary group) has about a random event taking place*" [1]. A Bayesian network is "*a compact and graphic representation of a joint distribution, based on some simplification of assumptions that some variables are conditionally independent of others*" [7]. As a result, the joint probability of a Bayesian network over the variables $U = \{X_1, \ldots, X_n\}$, represented by the chain rule can be simplified from Eq. (98.1):

$$P(U) = \prod_{i}^{n} P(X_i|x_1, \ldots, x_{i-1}) \tag{98.1}$$

where $P(U) = \prod_i^n P(X_i = x_i)$, the parents "(Xi)" is the set of parents of Xi. This property makes Bayesian networks powerful tools for the representation of domains in uncertainty conditions, which allows to calculate joint and marginal distributions more efficiently. The a priori probabilities must be taken into account, for this, an a priori probability distribution of a variable is taken, according to Eq. (98.2):

$$P(A) = \sum_{x_i} \ldots \sum_{x_k} P(X_1, \ldots, X_k, \boldsymbol{A}) \tag{98.2}$$

where A is the query variable, X_1 of X_K are the remaining variables of the network. This type of query can be used during the design phase of a tunnel, for example, to assess the probability of failure in design conditions (geology, hydrology, etc.). The posterior distribution of variables given the observations according to Eq. (98.3) must also be considered:

$$P(A|\boldsymbol{e}) = \frac{P(A, \boldsymbol{e})}{\sum X_i \ldots \sum X_k \sum AP(X_1, \ldots X_k, \boldsymbol{A}, \boldsymbol{e})} \tag{98.3}$$

where e is the vector of all the tests, and A is the query variable and X_1 to X_K are the remaining variables of the network. This type of query is used to update the knowledge of the state of a variable (or variables) based on the state of the other variables. It could be used, for example, to update the probability of a tunnel failure, after construction has begun, when new information about the geology is released.

In recent years, the Monte Carlo technique has been widely used to simulate risk events in different methodologies that analyze time, cost and scope variables related to the impact of each of them. Having this impact, the product with its respective probability of occurrence is calculated, resulting in the value of the risk according to a certain activity. This method includes the determination of a probability distribution of the variable to be treated to, then, obtain a sample of that distribution by random numbers. This series of random numbers generates a series of values that have the same distribution characteristics of the real experience that wants to be simulated. The outputs of the simulation show the possible duration values of the activities that have had a possible materialization of one or several risks represented in probability distributions [8].

The current planning and programming tools are based on deterministic models, such as the critical path method (CPM) which has been commonly used in practice due to its simplicity and has been adopted by most commercial software of project management. However, CPM has been widely criticized for its inadequate handling of the uncertainty inherent in construction projects [9]. Probabilistic methods, such as program evaluation and technical review (PERT) and Monte Carlo simulation (MCS) have been introduced as a supplement to the CPM to model the uncertainty inherent in construction projects. Both PERT and MCS assume durations of activities that are random variables and can be represented by probability distributions [9]. For this, it is necessary to generate probability density functions based on historical data, which makes the process cumbersome. For this, estimates of three points are taken (possibilities, optimistic and pessimistic). When these times are calculated, they tend to be optimistic, to remedy this trend the MCS is applied, providing more reliable estimates with probabilities that affect the critical path. Two objectives in the development of risk integration in programming are defined. First, is to increase the days of programming by explicitly incorporating the impact of the risks in the estimation of the duration of the activity, and second, to develop an effective programming and planning procedure that responds to risks [9].

The contingency is also modeled with the logic technique according to the activities affected by risks. The impact of the multiple risks in an activity can be determined, this makes it possible to make the comparison between the duration of the real project and the duration of the contract by reviewing the difference of both durations. The PERT method requires multiple estimates for task durations, considering the duration of tasks with random variables with a Triangular or Beta probability density function [10]. The concepts of the PERT model, detail that the tasks of the project are independent. This assumes that the estimates of the duration of the tasks should be executed independently of what may happen in other tasks in the project, which in turn may affect the availability of the resources provided for the task in question. PERT does not provide the probabilistic density function of all the tasks to the Project Managers, these are given by consensus of knowledge the 3 time parameters c, b, m. very similar to a triangular distribution with its 3 parameters (minimum, most probable and maximum duration).

98.3 A Methodological Proposal for Risk Analysis in the Construction of Tunnels

The proposed methodology for the risk assessment in excavation projects is developed in nine steps.

98.3.1 Risk Identification

The Risk identification is developed by an interdisciplinary group, which must be composed by professional and experienced workers capable to identify any type of risks. Then, a Risk Breakdown Structure (RBS) should be developed considering all the risks detected.

98.3.2 Qualitative Risk Assessment—Risk Nesting

The interdisciplinary group should create a matrix in which risk impact and risk probability must be rated in a qualitative way, for each risk considered in step 1. This is done in order to classify each risk depending on its impact and probability. The group defines the rating scale of the probability and the impact, stablishing an adequate number of scale levels. The impact is measured as time units in which the project is delayed and, to assign the scale levels for it, the group must consider percentages of the project length. To assign scale levels for the probability, the group must consider percentage ranks between 0 and 100% of occurrence of the risk event. After finding the value of the probability and the impact of each risk, the value of the risk should be calculated using the Eq. 98.4:

$$R = P \times I \tag{98.4}$$

This should be done with the qualitative values. This results in a classification of the risks that should be a priority for further quantitative analysis.

98.3.3 Risks/Activity Matrix

The analyzed risks and the project schedule activities are related. This is done to determine how the risks affect the critical activities of the project.

98.3.4 Quantitative Risk Assessment—Probability (Bayesian Networks)

Based on the model proposed by Špačková and Straub [2], in which they use Bayesian networks to model a tunnel construction process, particularly the time required for the excavation process under uncertain geotechnical conditions and varying time units, two processes should be taken into account:

- Definition of technical and geological specifications of the tunnel: Experts should collect all the geological information to classify the terrain, its dimensions, define excavation type and critical sections.
- Bayesian network development by tunnel sections: Considering the preliminary information, the Bayesian network should be structured to obtain the probability for each risk for each type of terrain defined in the previous process, taking into account the methodology proposed by Castillo [1], who builds the network in the following way:
  - Identification of relevant variables to explain the variables to be analyzed.
  - Build a network taking into account the causal relationships between the variables.
  - Verify the assumptions of conditional independence and the absence of circular relationships.
  - Define the conditions of the variables.
  - Estimate the probability of non-dependent variables (the concepts of the interdisciplinary group, historical concepts of other similar projects, among others, are used).
  - Estimate the conditional probability distribution of the dependent variables. To do so, an order of importance is stablished between the predecessor variables that are being analyzed.
  - Validate the consistency and structure of the networks by reviewing compliance with Bayesian network properties [7].
  - Evaluate the network through a specialized program.
  - Analyze the results and execute the adequate sensitivity analyzes for the important variables that relate the variables of interest.

After building the network, the data of the probability distribution of each analyzed variable is extracted in order to relate it to the respective risk. The results of the variable—risk are determined as a Bernoulli probability function, whose result is defined in 2 values (It occurs-It does not occur). This value will later provide information to the simulation and quantification matrix of the risk by activity.

98.3.5 Quantitative Risk Assessment—Impact

A probability function is defined which is determined as a time value that has affected each activity in days. For this application, a triangular function should be used considering the most optimistic, the most pessimistic and the most probable durations. These values are found considering the interdisciplinary group concepts; however, data from other projects can be obtained to observe the behavior of each duration.

98.3.6 Risk Value Calculation

The risk value should be calculated using Eq. (98.4) with the quantitative values. The entries for the simulation model are the following [8]:

- Estimation of the duration of the impact for each activity, without including any forecast or unforeseen.
- Scheduling of the project.
- Risks considered, including the risk classification in the qualitative analysis.
- Risk/Activity Matrix.

To obtain the results of the probable adjusted days and their respective probability of occurrence, the basic steps to simulate using the Monte Carlo method are the following:

- Risk events are characterized by their probability and Impact on the duration of the activity.
- Identify the activities that are affected by any of the determined risks.
- Considering the risk weighting for each activity, it is observed that an event may or may not occur, or a risk can be materialized. When the probability is 1 (100%), the event occurs all the times the model is run, however, when this value is lower, the event or risk occurs the percentage determined in each model run.
- Since the Impact has been quantified in three values (e.g.: 94% optimistic: 100% probable, 107% pessimistic), a probability density function must be assigned according to this data (e.g.: triangular distribution).
- In each subsequent iteration, the Monte Carlo model randomly chooses a multiplier according to the chosen probabilistic distribution. For these iterations, the factor that results from this operation multiplies the duration of the activities in which the risk materializes. Taking into account the probability of occurrence of the event, the multiplying factor in the Monte Carlo model should be related to the productivity of the affected day and its respective value.
- Obtain the respective graphs which must be evaluated to analyze the results.
- When the data of the model iterations are obtained, the project schedule is evaluated according to the critical route of the same.

The outputs of the simulation result in the possible duration values of the activities that have had a possible materialization of one or several risks represented in probability distributions. This can determine the probability of finishing the project and if the stablished deadlines can be reached, so a forecast value can be calculated in time with a more adjusted and real level. To define the forecast, a triangular probability function will be stipulated in the application for each activity related to its respective risk. For the assumption of the simulation, is necessary to define the rules as the risks occur, taking into account their probability of occurrence, which is an entry data. These rules were defined by the interdisciplinary group as follows:

- Criteria for obtaining maximum values when risks occur in parallel or when one occurs approximately in time with another as illustrated in Eq. 98.5:

$$Max(X_1, X_2, X_3, \ldots X_n) \tag{98.5}$$

- Value addition criteria when risks can occur in series, or when one occurs, then the other, as shown in Eq. 98.6:

$$\sum_{n}^{1} X_i \tag{98.6}$$

- Mixed criteria when the risks occur in parallel or series as a whole. In this case maximum values are taken within a sum of values according to their possible occurrence, as shown in Eq. 98.7:

$$\sum (X_1, X_2, \ldots X_n \ \max(Y_1, Y_2, \ldots Y_n)) \tag{98.7}$$

The foregoing depends exclusively on the position that the Contractor adopts against the risk. There are 3 options: Prone to risk (Add the values of the risks, minimum values or their combination), Neutral risk (Average risk values) and Risk aversion (Add the values of the risks, maximum values or their combination).

When the probability of occurrence is found by the Bayesian network method, it is being determined how the risks can be materialized. For the purposes of the proposed methodology, the Interdisciplinary Group should define the criterion to be taken regarding the interaction of each risk with each activity. Subsequently, the project schedule should be analyzed and its relationship with the occurrence of the activities. This analysis must be carried out by activity, by sub-milestone, milestone and total time of project duration in a staggered manner.

98.3.7 Data Review and Adjustment to Entry Project Data

When the values have been determined in days of the materialization of the risk for each activity, a data review and adjustment to entry project data must be done. The congruence of the data should be checked against the durations of each one, respectively. If they are right, the time buffers are added to the schedule and, if they are not, it is necessary to review the Bayesian networks.

98.3.8 Scheduling Adjustment with Time Buffers

The respective adjustment to the schedule should be done. This is done taking into account the values of time addition by milestone. It is not executed by activity considering that it would be very cumbersome and not practical for the programmer to add extra times for each activity. By milestone, a better versatility is reached since the buffer can be visualized in a more explicit and clear way. In addition, a better planning of the prevention, correction and contingency plans to be applied in the project can be projected.

98.3.9 Results Revision

To verify the results, is very important to observe the coherence of these against the duration by milestones and total of the project. The percentage margin of the total extra days that could be incurred in the schedule is determined. This percentage depends on the position that the organization took before the adoption of the risk. The organization review, according to their experience, the establishment of control measures, prevention against the materialization of the risks previously found.

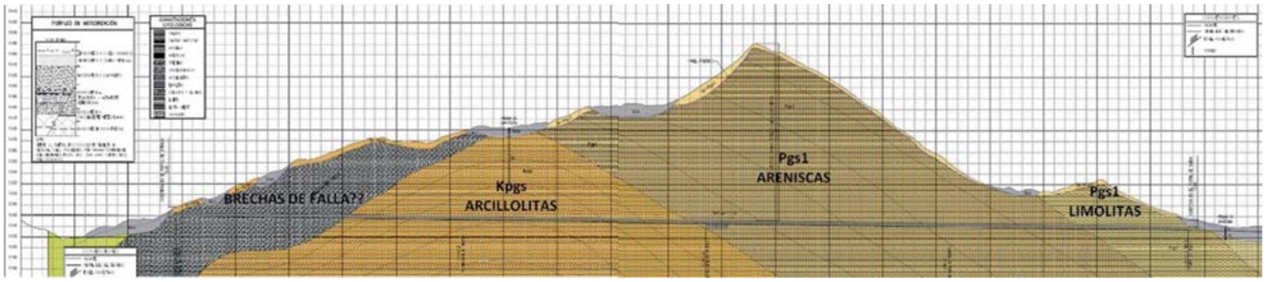

Fig. 98.1 Cut plane of one of the tunnels showing the excavation terrains

98.4 Application of the Proposed Methodology

The proposed methodology is currently being tested in the construction of two tunnels which belong to one of the 4G roads located in a town named Guaduas. The cut plane of one of the tunnels is shown in Fig. 98.1.

An interdisciplinary group of geologists, civil and environmental engineers, maintenance, equipment, safety, scheduling and management professionals, was formed to identify risks related to the project. Then, the RBS, the qualitative risk assessment and the Risk/Activity Matrix was done. The Bayesian networks were formed and developed using the program *Hugin Lite 8*. The most probable risks found were “Excavation profile collapse due to soil failure” in sandstone and claystone soils, and “Community social strike”. The interdisciplinary group defined, in the quantitative risk assessment, the most probable, optimistic and pessimistic durations for every risk. Considering the Probability and Impact for every risk, the risk value calculation was done using the Monte Carlo simulation developed in an Excel workbook using the application *Crystal ball*. The results of the simulation show that the mean value for Tunnel 1 was 133 delay days (with Beta function adjustment) and 183 delay days for Tunnel 2 (with Weibull function adjustment). Since the project is being currently developed, the results of the validation of the methodology are proposed for future research.

98.5 Conclusions

- The proposed model shows that it is possible to relate the time variable (total duration of programming) with the risks detected in the process of risk identification, linked to the planning of projects.
- It is recommended, in order to determine a more detailed assessment of each risk and in each activity, a more exact formulation could be set up to have the possibility of simulating it, thus the model would not depend too much in the concepts of the interdisciplinary groups.
- In the future, the information should be extracted from projects historical data, in order to form databases to work with more closed and less biased reliability margins.
- Management must have a deeper decision making process to choose its risk treatment, either by preventing, mitigating or transferring it according to its policy and risk appetite for the execution of its projects.
- This methodology could be extended for another type of project such as roads, bridges, industrial assemblies. It is necessary to review the steps and, in particular, the determination of the Bayesian analysis since here it is stablished by geographically affected section, in other projects the standardization and homologous behavior of some activities could be visualized in order to define the rules of interaction of the risks and your activities on the critical route.

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