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# Quantitative Risk Analysis for Construction Projects Considering Risks Correlations and Fuzzy Logic

# Análisis cuantitativo de riesgos para proyectos de construcción considerando correlaciones entre riesgos y lógica difusa

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**Abstract**

Construction projects have a high level of uncertainty because of several risk factors. Risks may affect projects in many ways resulting in time delays or cost overruns. Thus, the evaluation of uncertainty is required to get a reliable schedule. This research proposes a method for project scheduling considering risks. Expert judgment is used to identify and analyze risks. Potential risks are identified through Failure Mode Effect Analysis (FMEA). Risks impact is evaluated through fuzzy logic and Monte Carlo Simulation (MCS). The simulation considered the relationship between risks, and risks and activities.

**Keywords:** Construction Projects; Critical risks; Failure Modes and Effects Analysis; Fuzzy logic; Monte Carlo Simulation; Project scheduling; Quantitative Risk Analysis; Risk Correlations; Risk management; Uncertainty.

**Resumen**

Los proyectos de construcción sufren un alto nivel de incertidumbre debido a múltiples factores de riesgo. Los riesgos incertidumbre para tener programaciones confiables. Esta investigación propone un método para la programación de proyectos considerando los riesgos. Se aprovecha el juicio de expertos para identificar y analizar los riesgos. Los riesgos potenciales son identificados a través del Análisis modal de fallos y errores (FMEA). El impacto de los riesgos se evalúa a través de lógica difusa y simulación Monte Carlo (MCS). La simulación considera la relación entre riesgos y entre riesgos y actividades. La aplicación del método en un proyecto de construcción permitió obtener una programación más precisa.

**Palabras clave:** Proyectos de construcción; Riesgos críticos; Análisis modal de fallos y efectos; Lógica difusa; Simulación Monte Carlo; Programación de proyectos; Análisis Cuantitativo de Riesgos; Correlaciones de riesgo; Gestión de riesgos; Incertidumbre.

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## 1. Introduction

In Colombia, the construction industry is divided into buildings and civil work subsectors. Building subsector comprises residential and non-residential buildings. Civil work includes highways, bridges, and big engineering work. The construction industry is one of the most dynamic in the country.

Civil work is usually conducted through public work contracts under Design-Bid-Build (DBB) method. In this industry, projects have high financial investment restricted to time requirements. But these projects often have problems. On the one hand, the project duration may last 25% more than planned. The main reasons are scope changes and unconsidered risks [1]. Mckinsey estimates that 98% of megaprojects suffer cost overruns of more than 30%. And 77% of the projects are at least 40% late. Reasons are insufficient risk management, poor short-term planning and poor organization among others [2]. HKA, a consultancy specialized in risk mitigation and dispute resolution, has analyzed 1,800 projects in 106 countries. Top causes of conflicts are: unforeseen physical conditions, changes in scope and incorrect design. Risks have resulted in high disputed costs representing over 33% of capital expenditure, more than a third of projects value [3].

Another issue is culture. The culture in public work is oriented to only follow the regulatory framework. Plans are based on low quality previous studies and designs [4]. Poor studies, inadequate planning and poor contingency analysis also affect projects [5].

Risk management covers the processes to mitigate the impact and likelihood of contingencies. It includes the identification, analysis, responses, and control [6], [7], [8], [9].

The identification of risks is a critical phase. Non-identified risks are dangerous for achieving project objectives with harmful consequences [10]. Some methods are checklists, brainstorming, surveys, documents review and SWOT analysis [11], [7], [12]. Interviews and surveys are broadly used in construction projects research [13], [14], [15], [16], [17], [18], [19].

The analysis of risks covers the understanding of their sources and potential impacts. This last activity helps to understand risks and to identify response strategies. Several categories have been developed in construction literature as seen in Table 1.

Table 1. Risk categories

| Source | Categories of risks |
|---|---|
| [20] | Natural environment, Construction technology, Project management, Security management, Financial |
| [7] | Technical, Management, Commercial, External |
| [21] | Technical risks, Project management risks, Financial risks, Environmental risks and External risks |
| [22] | Environmental factor, Alternative Method, Labor Resources, Alternative Metode/Desain, Activities, Work Package, Tool Resources, Material Resources |
| [23] | Political Environment, Law and regulations, Construction equipment |
| [24] | Sources, project phases |
| [19] | Owner-related factors, Consultant-related factors, Design team-related factors, Materials-related factors, Labor-related factors, Contractor-related factors, Project-related factors External factors, Plan/equipment-related |
| [25] | Acts of God risks; physical risks; financial and economic risks; political and environmental risks; design risks; job site-related risks |
| [26] | Financial, managerial, construction, design, operational, and safety and health |
| [15] | Owner, contractor and design engineer categories |
| [27] | Internal Risks: Owners, Designers, Contractors, Sub- Contractors, Suppliers. External Risks: Political, Social & Cultural, Economic, Natural, Others |
| [9] | Environmental: Economy, Social, Regulatory, Technology. Internal agents: People, Materials, Equipment, Facilities. |

The analysis of risks is followed by the analysis of the impacts of those risks. This analysis can be conducted by qualitative or quantitative approaches. Qualitative analysis is the process followed to prioritize the project identified risks. This allows the project manager to make decisions. Specific response strategies may be used for important risks, while accepting the rest. Techniques applied in construction research are: multicriteria analysis (AHP, and PROMETHEE), fuzzy analysis, relative importance index (RII), risk matrix, and Failure Mode and Effects Analysis (FMEA) [28], [29], [30],

[31], [32], [33], [15], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46].

Quantitative analysis numerically estimates the risk effect over project time or cost. Techniques applied in construction research are Monte Carlo simulation (MCS), Bayesian believe networks (BBN), neural networks, Markov chain and mathematical models [47], [48], [49], [50], [51], [52], [53], [54], [40], [55], [56], [57], [58], [59], [60], [61], [62], [63].

The purpose of this research was to study the impact of risks over the project schedule. This, considering the relationship between activities and risks in the Colombian construction environment. Following those steps, this research identified potential risks from the literature. Later, the qualitative analysis identified critical project risks. And finally, the quantitative analysis identified the impact of correlated risks.

## 2. Methods

The approach for the research followed the general process of risk management. Authors in the construction field propose similar steps with some variations. The first step is usually risk identification.

Several proposals were found for the rest of the process. Potential steps are control, and opportunities exploitation [64], [65], [66], [67]. Risk assessment, risk response plan, and risk response control [68], [69]. To assess risk, risk responses plan and track and risk control [70], [71]. Risk quantification and risk control [72], [73]. And risk quantification and risk mitigation strategies [66], [65], [74]. In these cases, the analysis of impacts is mainly performed by qualitative methods. The last part of the process is the design of responses and their control later.

The method covered identification, prioritization, and evaluation considering the particularities of the project. The research did not consider the design of responses and control. To conduct the research, potential risks were identified and categorized. Potential risks in construction projects were found in a literature review. Sources reviewed were Science Direct, EBSCO, Scielo, and Emerald. Keywords were delay causes and schedule risks in construction and highway projects.

This input was adjusted to the local construction environment through an expert panel. This allowed the extraction of risks repeated and included in others. Finally, those risks were categorized to facilitate the analysis. The second phase was performing the qualitative analysis. This allows deciding which risks should be used in the quantitative analysis. To this end, the method applies the Failure Mode Effect Analysis (FMEA). It uses likelihood, impact, and detection attributes for every risk to build a risk priority number (RPN). The analysis is conducted through an expert panel.

Finally, it was conducted a quantitative analysis. It was applied MCS and fuzzy logic to include uncertainty in activities duration. The first step was gathering the project schedule information. The second step was gathering project risk information. Risks correlation, probability limits, the scale of activity-risk influence degrees and the activity-risk influence corresponds to that information. After that, the simulation model was built, and a sensitivity analysis was performed.

## 3. Results

The method was applied in a construction project from the building subsector. The purpose of the building was to offer a group of street vendors a better health condition place. The project had two phases: design (plans, budget, and programming) and construction work.

The bid established a short timeline of six months starting on April 28th 2015. So, the stipulated deadline was October 28th 2015. Nonetheless the project needed more time because of several change orders. In the following, the findings and the analysis of change orders are presented.

### 3.1. Identification and Categorization of Risks

The literature review allowed to identify 14 papers related to the topic. Surveys and interviews are the most used methods. There were found 650 risks in construction projects.

This initial list was adjusted by extracting repeated and included in others. The list was adjusted to 209 risks. The following Table 2, shows the sources of the potential risks for the project.

Critical risks are the risks that may be considered in the project. The expert panel identified those risks that could happen in the local context. The panel consisted of three engineers from the contracting party. Finally, the risk list was reduced to 109 risks.

A project life cycle includes the planning, execution, and delivery phases. The life cycle of a construction project has certain particularities. The phases used in the research were formulation, pre-contractual, contractual and construction.

Table 2. Risks sources

| Risks | Authors | Risks | Authors |
|---|---|---|---|
| 21 | [80] | 82 | [77] |
| 58 | [91] | 30 | [82] |
| 293 | [79] | 30 | [81] |
| 70 | [83] | 36 | [85] |
| 99 | [86] | 62 | [87] |
| 61 | [78] | 28 | [89] |
| 8 | [84] | 37 | [76] |
| 73 | [90] | 23 | [88] |
| | | 51 | [75] |

The final risk list was categorized according to those phases. It resulted in formulation (37 risks), pre-contractual (2 risks), contractual (one risk) and construction (69 risks). The last category was then used for the qualitative analysis.

### 3.2. Qualitative Analysis

This analysis was conducted through the FMEA method in an expert panel. The method analyses likelihood, impact, and detection attributes of every risk. The scale used was adjusted from Santos and Cabral [92] and Carbone and Tippett [46] in detection difficulty as seen in Table 3.

The Risk Priority Number (RPN) is the product of the likelihood, impact, and detection risk factors. This metric allows having only one risk value to build a ranking better than using the three factors. The next figure shows the Pareto chart built with RPN values.

The Pareto analysis found that only 7 risks corresponded to 42,6% of the accumulated RPN as seen in Figure 1.

However, the research applied 31 risks that corresponded to 80% of the accumulated RPN as seen in Table 4.

Table 3. FMEA Categories

| | Value | Description |
|---|---|---|
| Likelihood | 5 | Very likely to occur. |
| | 4 | Will probably occurs. |
| | 3 | Equal chance of occurring or not. |
| | 2 | Probably will not occur. |
| | 1 | Very unlikely. |
| Impact | 5 | Major milestone and critical path impact. |
| | 4 | High milestone and critical path impact. |
| | 3 | Moderate milestone and critical path impact. |
| | 2 | Low milestone and critical path impact. |
| | 1 | Impact insignificant. |
| Detection Difficulty | 5 | There is no detection method available or known that will provide an alert with enough time to plan for a contingency. |
| | 1 | Detection method is highly effective, and it is almost certain that the risk will be detected with adequate time. |

### 3.3. Qualitative Analysis

This analysis used Fuzzy logic and MCS to include uncertainty in activities duration. MCS also included risk-risk and risk-activity relationships. The information required was the project schedule and risk relationships. Finally, the model was simulated in several instances to test results sensitivity. Information required for the model was as follows:

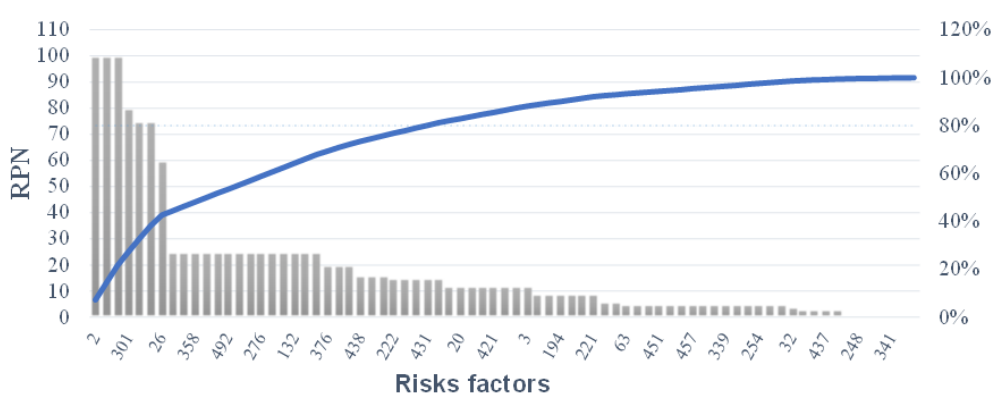


Figure 1. Pareto Chart.

Activities, duration and precedence relationships. The contracting party provided the schedule information produced after the design phase. The project had a deadline of 180 days, including designing and building. But, after the design phase, the new deadline was 568 days. The expert panel estimated fuzzy data, minimum, most likely, and maximum activities duration.

Correlated risks. Correlated risks. The expert panel identified the following nine correlated risk groups:

Group 1: Delays in material supply, Unreliable suppliers, Restriction on capital transactions Relation with the third party, Delayed payments, Difficulty in choosing a business dealer.
Group 2: Weather conditions and other natural delay causes, Late handing over of the site, Inadequate project management assistance, Ineffective project planning, and scheduling.
Group 3: Equipment quality, Shortage in machine tools and workers mobilization due to clashes of several projects.
Group 4: Earthquake.
Group 5: Fire.
Group 6: Social conditions (e.g. population density & wealth distribution), Safety regulation.
Group 7: Material theft & damage, Changes in material types and specifications during construction, Bad quality of workmanship.
Group 8: Infrastructure damage caused by irresponsible people, Inappropriate contractor's policies, Low motivation and morale of labor, Low productivity of labor.
Group 9: Cost Overrun, Unexpected surface & subsurface conditions (soil, water table, etc.), Cash flow problem, Additional construction.
Group 10: Slowness in decision making, Loss of time by traffic control and restriction at the job site.

Risks probability degrees. Risks may occur as better than expected, expected or worse than expected [29]. The estimation of this variability range is between 0 and 1. Correlated risks received the same valuation.

Risks influence degrees. For every risk also, it was decided a scale of the potential influence that can be ineffective, effective, and very effective. The numerical valuation is from 0 to 100, as proposed by [40].

Risk-activity influence grades. The scale for this evaluation was ineffective, effective, and very effective as proposed by [40].

### 3.4. Simulation model

The model was built on the Palisade @Risk software. Input data were schedule and risk information. The schedule information was fuzzy duration and precedence relationships for every activity. Risk information was the correlated risks, risk probability degrees, risk influence degrees, and risk-activity influence grades. The output data was the fuzzy duration of the project and its upper and lower limits.

The fuzzy duration of the project has three values: lower, average, and upper duration. Nonetheless, uncertainty also affects those values that add minimum, maximum, and mean values. So, the duration is the lowest value of the lower limit, the average of the fuzzy duration, and the highest data of the upper limit.

After 1.000 runs, the simulation model produced the fuzzy duration of the project. The three durations were 490,14 days (lower limit), 573,35 days (average duration) and 598,91 days (upper limit) as seen in Figure 2.

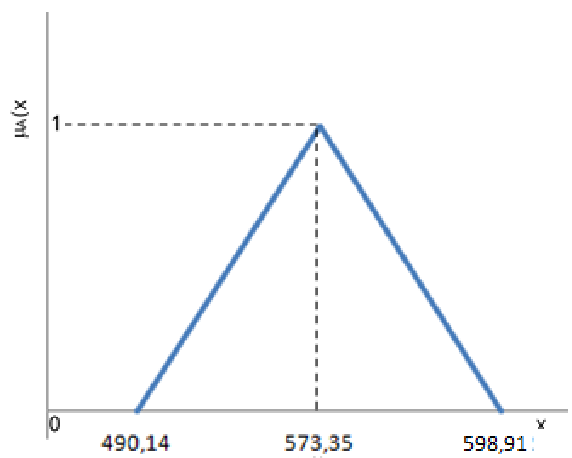

Figure 2. Fuzzy project duration (days)

The value of 573,35 days has the greatest possibility of being the duration of the project. Its degree of belonging is 1 in a membership interval of [0,1]. Values that are less than 490,14 and greater than 598,91 have a membership: mA (x)=0. This means that the element does not belong to the set. The duration of the project could be between 490,14 and 598,91 days. The duration values decrease as they move away from 573,35 and approaching 490,14 and 598,91 days.

Table 4. Critical risks

| ID | Risk | Category | RPN | % cum. |
|---|---|---|---|---|
| 2 | Cost Overrun | Economic and financial | 100 | 7,23% |
| 470 | Unexpected superface & subsurface conditions (soil, water table, etc.) | External related factors | 100 | 14,46% |
| 39 | Unforeseen ground conditions | Site conditions | 100 | 21,69% |
| 301 | Infrastructure damage caused by irresponsible people | External related factors | 80 | 27,48% |
| 373 | Weather conditions and other natural causes of delay | Environments | 75 | 32,90% |
| 154 | Late handing over of the site | Management - Planning | 75 | 38,32% |
| 26 | Additional construction | Project | 60 | 42,66% |
| 202 | Earthquake | Environments | 25 | 44,47% |
| 90 | Fire | Environments | 25 | 46,28% |
| 358 | Delays in material supply | Resources | 25 | 48,08% |
| 228 | Material theft & damage | Resources | 25 | 49,89% |
| 484 | Changes in material types and specifications during construction | Resources | 25 | 51,70% |
| 492 | Unreliable suppliers | Resources | 25 | 53,51% |
| 365 | Bad quality of workmanship | Resources | 25 | 55,31% |
| 113 | Too high-quality standard | Resources | 25 | 57,12% |
| 276 | Restriction on capital transactions | Economic and financial | 25 | 58,93% |
| 127 | Relation with the third party | Parties involved | 25 | 60,74% |
| 128 | Delayed payments | Parties involved | 25 | 62,55% |
| 132 | Difficulty in choosing business dealer | Parties involved | 25 | 64,35% |
| 318 | Social conditions (e.g. population density & wealth distribution) | External related factors | 25 | 66,16% |
| 214 | Safety regulation | Site conditions | 25 | 67,97% |
| 376 | Cash flow problem | Economic and financial | 20 | 69,41% |
| 503 | Slowness in decision making | Parties involved | 20 | 70,86% |
| 465 | Loss of time by traffic control and restriction at job site | External related factors | 20 | 72,31% |
| 438 | Inappropriate contractor's policies | Parties involved | 16 | 73,46% |
| 476 | Low motivation and morale of labor | Labors related factors | 16 | 74,62% |
| 477 | Low productivity of labor | Labors related factors | 16 | 75,78% |
| 222 | Equipment quality | Resources | 15 | 76,86% |
| 145 | Shortage in machine tools and workers mobilization due to clashes of several projects | Resources | 15 | 77,95% |
| 424 | Inadequate project management assistance | Parties involved | 15 | 79,03% |
| 431 | Ineffective project planning and scheduling | Parties involved | 15 | 80,12% |

It was also found that groups 2 and 9 are which have the greatest impact on the duration of the project as seen in Table 5. Group 2 has the highest incidence in the lower limit and in the average fuzzy duration of the project. While Group 9 has the greatest impact on the upper limit of the fuzzy duration of the project.

Risks from group 2 and group 9 occurred during the construction phase of the project. Risk events related to Group 2 affected the project, adding 218 days. While risks from group 9 affected the project in 210 days. Despite the expert panel identified those risks, their impact was bigger than considered.

Table. 5. Regression coefficients for the fuzzy project duration

| | Upper Fuzzy Duration | Average Fuzzy Duration | Lower Fuzzy Duration |
|---|---|---|---|
| Group 1 | 0,08 | 0,21 | 0,2 |
| Group 2 | 0,19 | 0,61 | 0,64 |
| Group 3 | 0,05 | | |
| Group 4 | | | |
| Group 5 | 0,08 | 0,08 | 0,05 |
| Group 6 | | | |
| Group 7 | | 0,05 | 0,14 |
| Group 8 | 0,2 | 0,15 | |
| Group 9 | 0,49 | 0,18 | 0,14 |

### 3.5. Simulation Results

As a sensitivity analysis, the behavior of the variables was studied under several scenarios. Simulations with 500 and 5.00 iterations were run considering risk correlations.

The average duration is the same for the correlation and non-correlation scenarios, as seen in Table 6. The lower limit and the average duration are the same for all correlated risk scenarios. The upper limit is one day different. The results have little variation when changing scenarios, so the model is stable.

Table 6. Project durations with different configurations

| Configuration | Duration lower fuzzy limit (days) | Duration average fuzzy limit (days) | Duration upper fuzzy limit (days) |
|---|---|---|---|
| Base simulation (1.000 iterations) | 490,14 | 573,35 | 598,91 |
| 500 iterations | 490,14 | 573,35 | 598,81 |
| 5.000 iterations | 490,14 | 573,35 | 599,82 |

Considering that the actual duration of the project was 658 days, the gap when compared to the contracted duration was 478 days. It corresponds to almost three times its planning. The same analysis but against the estimated fuzzy duration limit, 599 days, the gap was only 59 days, as shown in Table 7.

Table 7. Project analysis

| | Duration (days) | Delay (days) | Delay (%) |
|---|---|---|---|
| Awarded duration | 180 | 478 | 266% |
| Fuzzy duration | 599 | 59 | 10% |

As there was a design stage after the signing the contract, there was a new estimated duration. The duration estimated in the design phase was higher than the duration awarded. This results from the detailed design and schedule resulting in 568 days. This duration was in the range between the lower and middle limits of the simulation results. This estimate is within the fuzzy range of the model, but the contract was not changed. So, the original estimate of 180 days was the goal of the scheduling. The real duration exceeded all estimates because of risk events not considered before.

## 4. Conclusions

This research contributes in development of project scheduling including the impact of risks. Specific risks for the project are identified and evaluated. The use of critical risks in the scheduling method allows to conduct a detail analysis. Specific risks analysis is conducted to perform fuzzy logic simulation for project scheduling.

It was validated in a building construction project with the support of expert judgment. The results suggest that it may be obtained project estimated duration with minimum error. Schedules based on deterministic approaches without risk analysis may produce a lower duration.

Regarding risk prioritization, the model reduces the number of risks to work. The model takes advantage of the expert's knowledge with no need for historical data. There is a clear challenge for the application of expert-based methods. It depends on the willingness, commitment, and experience of the people involved. Also, the level in which the qualitative analysis may be performed may require a lot of time and effort to rank the potential risks.

Future research could consider other project objectives as costs or quality. Real project situations such as resource constraints may also improve the method.

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**Autor Contributions**

A. Cuadros-López: Conceptualization, Formal Analysis, Investigation, Writing – review & editing. N. Cruces-Arévalo: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing. C. Ortiz: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing.

All authors have read an agreed to the published version of the manuscript.

**Conflicts of Interest**

The authors declare no conflict of interest.

**Institutional Review Board Statement**

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