

## Article

# A Generic Framework for Managing Schedule and Cost Risks of Construction Activities Using PERT and the EV Technique

Essam Zaneldin <sup>1,\*</sup>  and Waleed Ahmed <sup>2</sup> 

<sup>1</sup> Department of Civil and Environmental Engineering, United Arab Emirates University, Al Ain P.O. Box 15551, United Arab Emirates

<sup>2</sup> Engineering Requirements Unit, United Arab Emirates University, Al Ain P.O. Box 15551, United Arab Emirates; w.ahmed@uaeu.ac.ae

\* Correspondence: essamz@uaeu.ac.ae

**Abstract:** Construction projects are complexity, multidisciplinary, have thousands of activities and details, and involve many participants. This intricate and fragmented nature of construction projects coupled with tight budgets and limited resources makes them good candidates for failure and promotes the emergence of risks. These risks must be addressed in the decision-making process and properly managed to mitigate their effect. However, risk management is one of the most difficult tasks and the assessment and analysis of the cost and schedule risks of construction activities are considered the most challenging tasks in the whole risk management process and require careful considerations throughout the life cycle of a project. Despite the high cost associated with managing risk in construction projects, the outcome of this task normally provides fruitful benefits. To address this crucial issue, this study employs a mixed methodology approach utilizing both qualitative and quantitative methods to gather feedback from construction experts and identify schedule and cost risk events associated with construction activities, prioritize their likelihood of occurrence, and suggest responses to mitigate them. The Program Evaluation and Review Technique (PERT) and earned value (EV) analysis are then used to estimate the expected cost at completion and the risk associated with it. A spreadsheet framework is then developed to help construction practitioners identify the most severe risks and measure their effect on the project's duration and cost. The framework also suggests risk responses for each of the risk events. The study then provides recommendations to mitigate risks with high impact and severity.

**Keywords:** construction projects; cost and schedule risks; earned value analysis; expert opinions; PERT; risk management



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## 1. Introduction

Historically, the concept of risk management was first addressed more than 2400 years ago, when the Greeks used to assess risks before making decisions [1]. Risk analysis of construction projects has its roots in the development of the Program Evaluation and Review Technique (PERT) in the 1950s for evaluating uncertainty in activity durations of projects. Principles and methods were developed to conceptualize, assess, and manage risks using both theoretical platforms and practical models and procedures. These attempts form, to a large extent, the foundation of this field today. However, risk management, as a field, is still considered relatively young with many concerns that need to be addressed [1,2].

The complex and fragmented nature of construction projects make them risky and good candidates for failure if risks are not managed properly [3]. Construction projects have multiple phases and involve many stakeholders, numerous details, technological advancements, and long durations [4]. These complexities entail significant interactions among internal and external parties and, consequently, generate many risk events, including discrepancies, errors, mistakes, and mismatches. These risk events often remain

unnoticed and result in rework in design and construction and always lead to delays and cost overruns [5]. This is in addition to other challenges and uncertainties like weather and site conditions, resource issues, financial constraints, contractual disputes, and communication problems. As a matter of fact, there are no risk-free projects and, when compared with other industries, it is well known that the construction industry has a poor reputation history in risk management. However, the assessment of risk and uncertainty in construction projects and their potential consequences have been largely overlooked due to the lack of reliable data related to their occurrence and reasons [6]. This is in addition to the fact that current risk mitigation practices in the construction industry often focus on dealing with risks when they happen while overlooking important risk mitigation factors. Effective mitigation involves proper planning, regular monitoring, stakeholders' engagement, flexible contracts, technology utilization, effective project control, and, most importantly, robust risk management.

The effective management of risks associated with construction activities is, therefore, crucial to bring projects to successful completion with minimum delays and cost overruns. This can be achieved by proactive risk planning, contingency measures, and the ability to adapt to unforeseen circumstances in order to minimize, share, transfer, or accept risks. Many research efforts have addressed the management of schedule and cost risks associated with construction activities. However, the focus of risk management in construction projects has traditionally been on subjective (qualitative) risk assessment, due to the difficulties associated with obtaining objective and realistic frequencies and probabilities [7,8]. This is true since every construction project is unique by nature, making researchers rely on subjective probabilities rather than objective likelihoods. Even when estimating contingencies in construction projects, an approximate percentage of risk is usually added to determine a project's bid price. This subjective judgment of using rule-of-thumb procedures to estimate risks is not enough and needs to be structured for a better risk assessment and management. It is clear, however, that the task of assessing and managing risks of construction activities is not an easy one.

The next section reviews previous research efforts related to managing project risks in general and risk events associated with the schedule and cost of construction activities, in particular. The main gaps found in the literature review and identified from the construction experts include the following:

- The construction industry is lagging behind other industries in adopting smart technologies for almost all of its processes in general and for risk management in particular.
- Many construction practitioners are not aware of and do not fully understand risk management techniques and how these techniques are used.
- There is an absence of objective methods for quantifying the monetary impact of risk events.
- The majority of the available risk management tools and techniques may not be applicable for the management of risks related to construction projects.
- Current quantitative risk analysis methods often rely on qualitative expert opinions. While this is acceptable, the process of acquiring experts' feedback should be dynamic and should always be updated.

The main objective of this research, therefore, is to address some of the important gaps found in the literature by answering the following four main research questions:

1. How to make construction practitioners fully aware of available smart technologies and risk management techniques?
2. Can a tool, specifically customized for managing schedule and cost risks associated with construction activities, be developed?
3. How to quantify the monetary impact of schedule and cost risk events related to construction activities using more objective tools?
4. Can the process of acquiring experts' opinions be dynamic and is it possible to update the database of experts' opinions periodically?

The originality, significance, and contribution of this study to the body of knowledge in construction risk management are significant and multifaceted. Despite the wealth of existing literature on construction risks, this study offers unique insights and practical advancements that distinguish it from previous research. In essence, one of the primary concerns regarding originality is the potential redundancy of the study within an already well-explored field. However, this study differentiates itself through several aspects. First, it employs a novel integration of qualitative and quantitative analysis techniques, combining expert feedback with robust analytical tools such as the PERT and the earned value (EV) analysis. This dual approach provides a comprehensive understanding of risk factors and their impacts, bridging the gap between theoretical risk assessment and practical application. Second, the development of a dynamic and practical framework for risk management is an original contribution. The proposed framework's four modules (risk severity matrix generation, project scheduling, quantitative risk analysis, and risk response) offer practitioners a structured yet flexible tool as they allow them to update the risk events database and risk severity matrix, making them practical, current, and dynamic. The framework also provides valuable responses and mitigation strategies tailored to specific risk events of construction projects. Third, the context of the study is another point of originality. Focusing on construction projects within the United Arab Emirates (UAE) provides new insights into risk management practices in a rapidly developing region known for its ambitious construction initiatives. This regional focus addresses a gap in the literature, offering data and findings that may differ from those studies conducted in more traditionally researched areas related to the UAE.

In summary, by demonstrating the effectiveness of this integrated approach, the study provides a new perspective on risk assessment and management that can be adapted and expanded in future research. The proposed framework offers a tangible and unique tool for construction managers, enhancing their ability to anticipate and mitigate schedule and cost risks and make well-informed decisions related to identified risk events based on their potential quantitative monetary impact on the project's cost and schedule. The presented example illustrates the framework's application in a hypothetical scenario, providing clear insights into its utility, practicality, and effectiveness. This practical contribution is particularly valuable in an industry where risk management practices can significantly influence project outcomes and success. This contribution enhances the body of knowledge and offers a foundation for future research and practical advancements in the area of construction risk management.

## 2. Literature Review

Early research efforts have addressed fundamental concepts and principles on how to assess and manage risk appropriately and, therefore, different approaches have been proposed for assessing construction project risks. Dey [9], for example, proposed a risk management system during the early stages of a construction project using the analytic hierarchy process (AHP) and decision trees. The system attempts to manage construction project risks using the expected monetary value of risk response strategies. The approach recommends risk response scenarios rather than quantifying the impact of these risks. El-Sayegh [10] identified, assessed, and allocated risks in the UAE construction industry. Laryea and Hughes [11] referred to a paradigm shift in risk assessment from "classicalism" to "conceptualism" using analytical tools. However, this shift did not result in a greater adoption of the analytical tools by the construction professionals. Clark and Besterfield-Sacre [12] developed a Bayesian belief network (BBN) decision model for risk assessment, which uses a probability and statistics-based approach and fully utilizes historical data. Qiao et al. [13] developed a model for estimating accident frequency based on empirical databases and fuzzy sets using binomial regression. Kim et al. [14] developed a BBN model to quantify the probability of construction project risks related to delays in Vietnam. Meacham [15] explored risk-informed performance-based approaches in Australia, New Zealand, and the USA to identify tolerable levels of risk, performance expectations, and

design criteria for building design. In another study, Linthicum and Lambert [16] utilized expert elicitation and geographic data to mitigate cost risks associated with infrastructure performance decline by comparing relative development probabilities against land values and access points. The effort of Li et al. [17], on the other hand, addressed the management of risks associated with modular construction, focusing on identifying risk factors and assessing the impacts of the identified risk factors on project cost and duration. Hwang et al. [18] investigated risk management in small projects in Singapore in terms of status, barriers, and impact on project performance. The results of this study indicated a relatively low level of risk management implementation in small projects, where “lack of time”, “lack of budget”, and “low profit margin” were prominent barriers. Also, the results revealed a positive correlation between risk management implementation and improvement in quality, cost, and schedule performance of small projects. Creemers et al. [19] presented an approach to determine indices that allow the ranking of project risks based on the impact they have on project objectives. An interesting study by Mouraviev and Kakabadse [20] identified the main risks associated with public–private partnership types of contracts in an ongoing project in Kazakhstan and highlighted the reasons behind risk allocation decisions. The findings of this study showed that the government has transferred most of the risks to the private sector partner. Hossen et al. [21] proposed a method that uses the AHP for assessing construction risks in nuclear power plants. Gunduz et al. [22] proposed a fuzzy logic system to quantify the probability of delay risks in construction projects in Turkey. Similarly, Muneeswaran et al. [23] used the concept of fuzzy logic to assess schedule risks in the Indian construction industry. Budayan et al. [24] developed a fuzzy logic method for assessing construction risks using previous experience and experts’ judgement. Farooq et al. [25] introduced a weighting function to quantify the cognitive errors in construction risk assessment. The results of this study revealed that opportunities are underestimated by 7.5% and threats are overestimated by 8%.

El-Kholy [26] used artificial neural networks (ANNs) to predict schedule risks and cost overrun in highway projects in Egypt. Similarly, Muizz et al. [27] developed a machine learning model for assessing schedule risks in tall building projects using ANNs and support vector machines. In another study, El-Rasas and Marzouk [28] investigated the risks associated with the delays in Egyptian residential projects and developed a MATLAB-based fuzzy model to predict project delays, using MATLAB 9.7 version. Gondia et al. [29] used machine learning algorithms to predict construction project schedule risks. Boateng et al. [30] investigated risk management practices in building construction projects delivery in Ghana. In this study, qualitative data were obtained through interviews and analyzed using fuzzy synthetic evaluation. Zhang et al. [31] emphasized the significance of building information modeling (BIM) in identifying cost and schedule risks. Zou et al. [32] noted that BIM could be utilized as a systematic risk management tool during the development of a project and serve as a data generator to allow other BIM-based tools to perform further risk analysis. Similarly, Sami Ur Rehman et al. [33] investigated the role of BIM in identifying and managing schedule risks. Hoseini et al. [34] developed a generic risk maturity model and validated the model through qualitative analysis and focus group sessions. Pham et al. [35] developed a risk management process for use by general contractors during the bidding stage of design–build projects.

More recently, Chatzimichailidou and Ma [36] summarized the existing literature on the application of BIM in the safety management of the construction industry in general and the safety hazards of modular construction. El Khatib et al. [37] investigated the significance of Business Information Management (BIM) as an approach to mitigate project risks during the various project stages. Zhao [38] investigated the evolution trend of construction risk management research topics and found that risk analysis methods have shifted from ranking risks toward examining the interrelationships among risks, where researchers pay more attention to an individual risk category. Mohamed et al. [39] presented a risk assessment structural equation modeling approach that focuses on the critical risk factors in mega housing construction projects in Egypt and their impact on time and cost from contractors’

perspectives. Alfadil et al. [40] reviewed 6384 articles and concluded that there has been a continuous growth in publications on construction risk and environmental research related to the handling of force majeure and environmental risks and risks associated with the coronavirus pandemic and how to mitigate its effects on the construction industry. An interesting study by Wang et al. [41] investigated the importance of artificial intelligence (AI) tools in managing risks in construction projects. The study used a hybrid multi-criteria decision-making framework based on the Delphi method, analytic network process, and technique for order of preference by similarity to ideal solution under a fuzzy scenario. The proposed framework offers an approach to quantify the relative importance of AI technologies based on expert opinions gathered during the Delphi process, whereas the fuzzy methodology is used to rank and select the most appropriate AI technologies for the construction industry. An interesting study by Antoniou and Tsioulpa [42] considered the common causes of construction contract claims to investigate the probability of occurrence and the perceived impact of these claims on the project completion time, its total cost, and quality.

It is well known that the construction industry is experiencing a technological shift driven by the fourth industrial revolution (Industry 4.0), aimed at introducing digitalization and automation in the industry for improved productivity [43,44]. Despite the valuable research efforts related to the issue of assessing and managing risks of construction projects, the construction industry is still lagging behind other industries in adopting smart technologies for almost all of its processes in general and for risk management in particular. In addition, while some contractors employ risk management practices, there is a need to overcome some of the main barriers to risk management implementation such as understanding risk management techniques, identifying the most frequent risk events, and estimating the probability of the occurrence, impact, and severity of such risk events [45]. Construction practitioners, in particular, remain concerned over the task of effectively assessing and managing risks associated with the project's schedule and cost [46]. To address this challenging task, it is important to understand the definition of risk management and investigate the techniques used to manage risks associated with construction projects. The following subsections address these two important issues.

### *2.1. Definition of Risk Management*

The Project Management Body of Knowledge (PMBOK) defines the risk management process as the “systematic process of identifying, analyzing, and responding to project risks. It includes maximizing the probability and consequences of positive events and minimizing the probability and consequences of adverse events to project objectives” [47]. The International Organization for Standardization (ISO) defines risk management as the “coordinated activities to direct and control an organization with regard to risk” [48]. The ISO definition emphasizes the need for a structured and systematic approach to identify, assess, and treat risks. The United States Department of Defense (DoD) defines risk management as “the iterative process of identifying, assessing, and prioritizing risks, followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events or to maximize the realization of opportunities” [49]. All of these definitions agree that risk management requires proper assessment and analysis of risk events, which require the selection of the appropriate tools and techniques to achieve this objective.

### *2.2. Risk Management Techniques*

There are a number of well-established tools and techniques used to manage risks in construction projects. Selecting the appropriate tools and techniques plays an important role in the success of the risk management process. Several professional organizations have prepared standards and guidelines for the potential tools and techniques that can be used in risk management. These standards include the ISO/IEC 31010:2019 [50], the SA/SNZ HB 89:2013 [51], and the PMI Practice Standard Project Risk Management [52]. The ISO/IEC

31010:2019 [50] indicates that risk assessment techniques should be appropriate to the situation or organization under consideration, provide results in a form which enhances the understanding of the nature of the risk and how it can be treated, and be capable of use in a manner that is traceable, repeatable, and verifiable [53]. In essence, all standards and guidelines support this argument and agree that risk management tools and techniques should be carefully selected, and the selection of the appropriate tool or technique depends on the nature of the risk, the required process, and the expected outcomes.

According to the PMBOK [47], the tools and techniques can be utilized during any of the five project risk management processes. The tools and techniques that can be used in the project risk management processes are summarized as follows: (1) risk management planning: expert judgement, data analysis, and meetings; (2) qualitative risk analysis: expert judgment, interviews, data analysis, interpersonal and team skills, risk categorization, the probability and impact matrix, hierarchical charts, and meetings; (3) quantitative risk analysis: expert judgment, interviews, interpersonal and team skills, representation of uncertainties, simulation, value management, sensitivity analysis, decision tree analysis, and influence diagrams; (4) risk response planning: expert judgment, interviews, interpersonal and team skills, strategies for threats and opportunities, contingent response strategies, alternative data analysis, cost–benefit data analysis, and multi-criteria decision analysis; (5) implementing risk response: expert judgement, interpersonal and team skills, and project management information systems; and (6) risk monitoring and controlling: technical performance analysis, reserve analysis, audits, and meetings.

However, there is a clear lack of research on the tools and techniques used for managing risks in construction projects and the extent of their usage, and on the knowledge and acceptance of new computer-based tools and techniques for risk management [53]. In fact, several research efforts have discussed risk management and its tools and techniques, yet very few have addressed their practical application in managing risks of specific construction project events and at which stage these tools and techniques can be used [54]. While there is a full range of tools and techniques identified by the ISO/IEC 31010:2019 standards [50], the SA/SNZ HB 89:2013 standards [51], and the PMI Practice Standard for Project Risk Management [52], construction practitioners do not use many of these tools and techniques [53]. The most common tools and techniques referred to in the literature include multi-criteria decision analysis, fuzzy logic and Monte Carlo simulation, Bayesian networks, checklists, interviews with experts, fault tree analysis, event tree analysis, the program evaluation and review technique (PERT), cost–benefit analysis including the earned value (EV) technique, analytical network process, and data envelopment analysis. While the mentioned tools and techniques are important to manage risks, researchers tended to use them in a very limited scope, raising concerns on the general applicability and relevance of some of the risk tools and techniques to the construction industry. A study conducted by Jepson et al. [53], for example, noted that approximately 50% of the risk management tools and techniques do not appear in any of the academic papers examined by the research team. The study also revealed that much of the research work in the literature was focused on developing tools for risk assessment or providing case studies that appear to be academically interesting but not actually utilized in the construction industry. It is obvious that, despite the availability of a wide range of risk management tools and techniques identified by several standards, many of these tools and techniques are not practical for use in managing construction risks. Also, a good number of these tools and techniques do not appear in the literature and the relevance and applicability of many of these tools and techniques to the construction industry is not clear yet.

The scope of this study is limited to the identification and analysis of schedule and cost risk events of construction activities, using both qualitative and quantitative techniques. The qualitative techniques used in this research include expert opinions and feedback through a questionnaire survey, risk categorization, a probability and impact matrix, representation of uncertainties, and data analysis, while the quantitative techniques used are the PERT and the earned value (value management) techniques.

### 3. Research Objective and Methodology

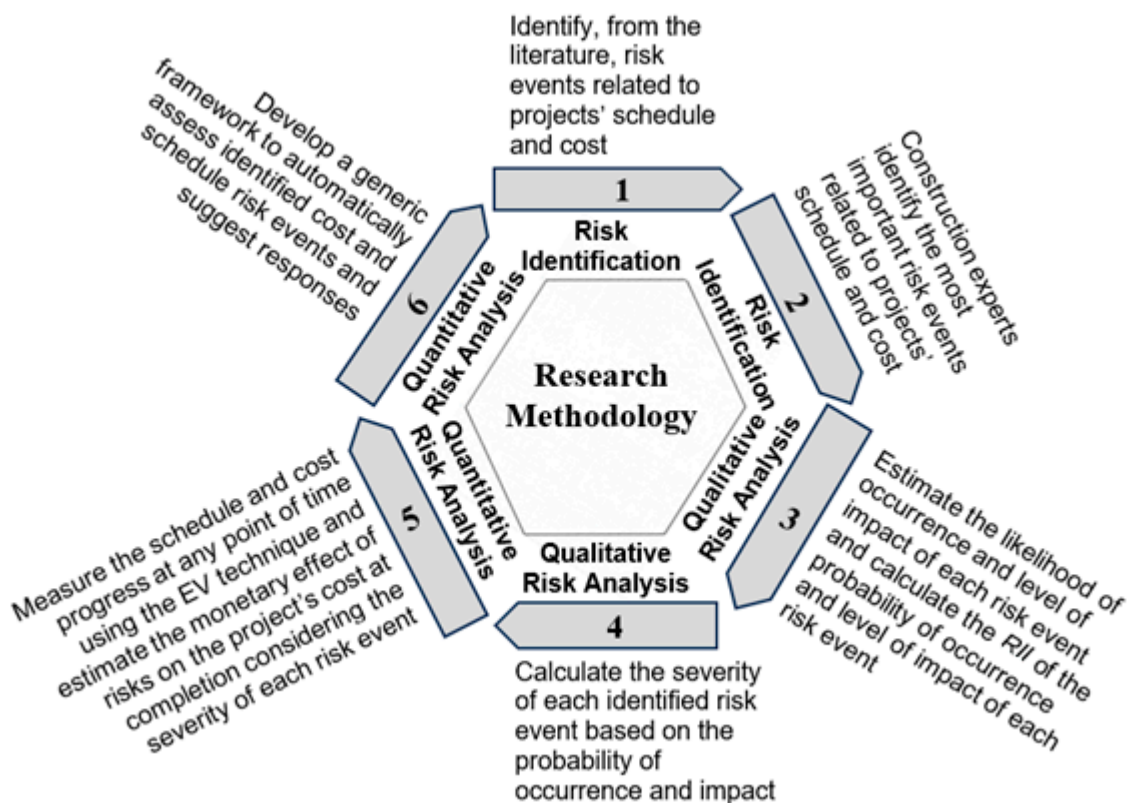
In view of the definitions discussed earlier and the gaps identified from the literature and from the survey respondents, this study presents a systematic approach to identify, analyze, and respond to schedule and cost risks associated with construction project activities. The main research objective is to address the gaps identified in the current literature, related to managing schedule and cost risk events of construction activities, by answering the four research questions listed in Section 1 by developing a practical and dynamic mechanism for effectively assessing the monetary impact of risks related to the cost and schedule of construction projects. The study was conducted following a systematic structured methodology. This study uses a combination of both qualitative and quantitative methodology to address the four research questions shown in Section 1. The methodology is summarized in Figure 1 and involves the following:

1. Previous research efforts were reviewed and 43 risk events that may affect projects' schedule and cost were identified.
2. Using the 43 risk events identified in item 1 above, an initial questionnaire survey was designed to elicit the feedback of construction practitioners in order to identify risk events and prioritize them, determine the probability of these risks happening, and estimate the degree of their impact. The survey was distributed to 68 practitioners from municipalities, contractors, and design offices in the UAE construction industry to provide their feedback regarding the most important schedule and cost risk events to be considered for further assessment and analysis. Construction practitioners were also requested to provide their feedback on the tools and techniques they use to manage risks associated with construction activities and the frequency of using these tools and techniques.
3. The majority of respondents who participated in the initial survey suggested 15 risk events as the most important ones among the 46 suggested in the initial survey. Considering these 15 risk events, a more detailed survey was then designed and conducted among the construction experts, who responded to the initial survey and committed to respond to the detailed questionnaire survey, to elicit their feedback on the probability of occurrence and impact of each of the 15 risk events. The data received from the survey respondents were then analyzed and most important risk events related to construction projects' schedule and cost were identified and analyzed as follows:
  - Identified risk events were assessed and the probability of occurrence of the risks was calculated. Identified risks were ranked by calculating the relative importance index (*RII*) of the probability of occurrence of each risk event.
  - The impact of each of the identified risk events was calculated and these risk events were ranked by calculating the *RII* of the impact of each risk event. Since the *RII* values of the probability of occurrence and impact of risk events were calculated based on a Likert scale range from 1 to 5, the values of the *RII* also had a 5-range scale (0% to <20%, ≥20% to <40%, ≥40% to <60%, ≥60% to <80%, and ≥80%), as shown in Table 1. The calculated *RII* values of the probability of occurrence and impact of risk events represent the level of occurrence and impact of each risk event.
4. The severity of each identified risk event was then calculated based on their probability of occurrence and impact. The level of severity of each risk event was determined based on the severity of these risk events resulting from the calculated probability of occurrence and level of impact of the risk events.
5. The "PERT" technique was used to perform a qualitative analysis of the impact and severity of risk events. The "EV" technique was then used to measure the schedule and cost progress at any point of time and quantify the monetary effect of risk events on the project's cost at completion, considering the severity of identified risks. This task addresses research questions 2 and 3.

6. In response to research question 4, a generic spreadsheet framework was then developed to automate the whole process in a dynamic environment. The dynamic framework performs the following tasks, addressing research questions 1, 2, 3, and 4:
- Measures the qualitative *RII* of the probability of occurrence and impact of each identified risk event and their corresponding levels of severity.
  - Allows users to update the responses database and the severity risk matrix, which can change based on the input of construction experts, making the process current and dynamic. This task responds to research question 4 (Section 1).
  - Calculates the quantitative monetary effect of these risks on the project's duration and cost, considering the estimated severity of identified risk events. Depending on the type of risk, some response actions can be suggested to mitigate risks and reduce their impact and severity.
  - Validate the proposed framework by requesting construction practitioners to use it in real life construction projects in order to familiarize them with this tool and increase their awareness of the benefits of such risk management tools.

**Table 1.** Levels of occurrence and impact of risk events.

Likelihood of Occurrence	Impact	RII
Rare (RAR)	Insignificant (INS)	<20%
Unlikely (UNL)	Minor (MIN)	≥20% to <40%
Possible (POS)	Moderate (MOD)	≥40% to <60%
Likely (LIK)	Major (MAJ)	≥60% to <80%
Almost Certain (ALC)	Catastrophic (CAT)	≥80%



**Figure 1.** Research methodology procedure.

The proposed framework was finally validated using a hypothetical example to illustrate its effectiveness as a practical and dynamic tool that can help project managers assess and quantify the impact of risk events of construction activities and suggest responses related to these risk events.

#### 4. The Questionnaire Surveys

The review of previous research efforts to investigate risks associated with construction projects resulted in identifying 43 risk events related to projects' schedule and cost. Two questionnaire surveys were conducted, an initial survey and a more comprehensive one. The purpose of the initial questionnaire survey is to identify the most important risk events rather than using a large number of unnecessary risk events.

##### 4.1. Initial Questionnaire Survey

The initial survey was conducted among 68 practitioners in the UAE construction industry to provide their feedback regarding the 43 schedule and cost risk events identified from the literature. The survey included eight questions (shown in Supplementary Materials), with the first two questions asking the participants about their organization and the locations of these organizations. The selected sample represents a wide range of geographical locations, as shown in Table 2. Feedback was received from 52 respondents from 8 municipalities (15%), 25 contractors (48%), and 19 engineering firms (37%), representing around a 76% response rate. The third question requested the participants to select their years of practical experience. The data received revealed that around 6% of the survey respondents have more than 15 years of experience, 52% have between 10 and less than 15 years of experience, 38% have between 5 and less than 10 years of experience, while 4% only have less than 5 years of experience. The fourth question asked the participants about their education degrees, and their responses revealed that around 63% of them have a bachelor's degree, 33% have a master's degree, while only 4% hold a PhD degree.

**Table 2.** Distribution of responses.

City	Surveys Distributed	Responses Received	Response Rate (%)
Abu Dhabi	27	21	78%
Dubai	25	19	76%
Sharjah	5	3	60%
Ajman	4	3	75%
Ras Al-Khaimah	3	2	67%
Al-Fujairah	2	2	100%
Umm Al-Quwain	1	1	100%
Al-Ain	1	1	100%
Total	68	52	76%

In the fifth, sixth, and seventh questions of the survey, construction practitioners were asked about their awareness of the tools and techniques used for risk management. Around 37% of the respondents indicated that they are not aware of any effective tools and techniques for managing risks related to construction activities, while the remaining 63% indicated that they avoid using such techniques. Construction practitioners often avoid using risk management tools and techniques for several reasons. One of the main reasons is that the majority of these tools and techniques are not applicable for construction projects and, therefore, construction practitioners find it difficult to adapt these tools to their specific project needs. Another reason is that many of these tools and techniques can be quite complex, requiring specialized knowledge, training to use effectively, and significant time to learn. Some practitioners even see risk management as an unnecessary overhead rather than a critical part of project management. Another important reason is the lack of awareness about the availability and benefits of various risk management tools and techniques. The last question requested participants to provide a rank in a scale from 1

to 5 for the importance of the 43 risk events, with 1 being “not important” while 5 indicates “very important”. The analysis of the data received is presented in Section 5.

#### 4.2. Detailed Questionnaire Survey

The detailed questionnaire survey included five important questions, as shown in Supplementary Materials. The survey was conducted among the 52 construction experts, who responded to the initial survey and committed to respond to the detailed questionnaire survey. The first two questions of this more comprehensive survey requested construction practitioners to provide their feedback on the probability of occurrence and impact of each of the most important 15 risk events identified by them in the initial survey. Their feedback was required on a 1-to-5 Likert scale for each deployed risk event, where 1 indicates a “very low” probability of occurrence or impact of each risk event while 5 represents a “very high” probability of occurrence or impact of the event. Question 3 requested construction experts to suggest responses to each of the 15 risk events, while question 4 asked them to provide generic strategies for mitigating risks related to construction activities. The last question of the survey requested the participants to provide comments, recommendations, or suggestions to improve the process of managing risks associated with construction projects. The detailed analysis of the data received is presented in Section 5.

### 5. Data Analysis

The responses were collected, and the data were analyzed for the identified 15 most important risk events related to projects’ schedule and cost. The likelihoods of occurrence for the 15 risk events, as received from the survey respondents, in a scale from 1 (rare) to 5 (almost certain) are shown in Table 3. For the “errors in the estimation of quantities and costs” risk event, for example, 4 respondents indicated that this event rarely happens (RAR), 6 indicated that the event is unlikely (UNL) to happen, 18 believe that the event happening is possible (POS), 11 think that it is likely (LIK) to happen, while 13 indicated that it is almost certain (ALC) that the event will happen.

**Table 3.** The likelihood of occurrence of the selected risk events.

Risk Event	Likelihood				
	1 (RAR)	2 (UNL)	3 (POS)	4 (LIK)	5 (ALC)
Late delivery of materials	3	8	15	14	12
Scope change (additions/deletions)	3	5	11	18	15
Efficiency, late arrival, and downtime of equipment	7	18	16	7	4
Rework due to design errors and conflicts in contract documents	10	13	10	11	8
Errors in the estimation of quantities and costs	4	6	18	11	13
Limited funds	12	20	10	6	4
Quality problems (poor quality and failure to meet specifications)	6	14	10	11	11
Availability of skilled resources	7	12	17	9	7
Complex design	10	14	16	8	4
Delay in the approval of materials and shop drawings	3	7	12	16	14
Poor coordination during design and construction	2	8	15	15	12
Poorly defined scope and inadequate design details	4	7	12	15	14
Weather conditions	14	16	15	5	2
Errors in the estimation of task durations	2	7	11	15	17
Different site conditions	11	18	16	4	3

Similarly, construction experts provided their feedback regarding the impact of each risk event on a scale from 1 (insignificant) to 5 (catastrophic), as shown in Table 4. For the same risk event (errors in the estimation of quantities and costs), 2 respondents indicated that the impact of this event is insignificant (INS), 8 indicated that the event's impact is minor (MIN), 15 think that the impact is moderate (MOD), 15 believe that the impact is major (MAJ), while 12 indicated that the impact of the event is catastrophic (CAT).

**Table 4.** The level of impact of the selected risk events.

Risk Event	Impact				
	1 (INS)	2 (MIN)	3 (MOD)	4 (MAJ)	5 (CAT)
Late delivery of materials	3	8	17	11	13
Scope change (additions/deletion)	2	10	14	14	12
Efficiency, late arrival, and downtime of equipment	3	7	13	15	14
Rework due to design errors and conflicts in contract documents	5	8	16	11	12
Errors in the estimation of quantities and costs	2	8	15	15	12
Limited funds	6	8	16	12	10
Quality problems (poor quality and failure to meet specifications)	6	10	17	11	8
Availability of skilled resources	4	7	16	12	13
Complex design	1	8	14	17	12
Delay in the approval of materials and shop drawings	6	9	16	12	9
Poor coordination during design and construction	6	11	17	11	7
Poorly defined scope and inadequate design details	3	5	14	16	14
Weather conditions	12	17	15	5	3
Errors in the estimation of task durations	6	7	15	12	12
Different site conditions	9	16	15	8	4

The *RII* for the likelihood of occurrence and impact were then calculated for each risk event to provide an indication of the importance of each particular risk event (argument) relative to other risk events (arguments) in the survey. The *RII* was calculated as follows:

$$RII_i^k(\%) = \frac{(n_1 + 2n_2 + 3n_3 + 4n_4 + 5n_5)}{(n_1 + n_2 + n_3 + n_4 + n_5)} \times \left(\frac{100}{5}\right) \quad (1)$$

where  $RII_i^k$  is the relative importance index of each risk event, “*i*” to “*k*” is the batch of respondents, and “*n*” is the number of responses received. The *RII* is used to classify the 15 risk events in terms of their probability of occurrence and impact as indicated by their *RII* percentage. The *RII* for the likelihood of occurrence of the “errors in the estimation of quantities and costs” risk event, for example, is calculated as follows:

$$RII = [(1 \times 4 + 2 \times 6 + 3 \times 18 + 4 \times 11 + 5 \times 13)/52] \times (100/5) = 68.8\%,$$

which indicates that this risk event is likely to happen (LIK), as illustrated in Table 1.

Similarly, the *RII* for the impact of the “errors in the estimation of quantities and costs” risk event, for example, is calculated as follows:

$$RII = [(1 \times 2 + 2 \times 8 + 3 \times 15 + 4 \times 15 + 5 \times 12)/52] \times (100/5) = 70.4\%,$$

which indicates that the impact of this risk event is major (MAJ), as illustrated in Table 1. The *RII* percentages for the probability of occurrence and impact of the 15 risk events

are listed in Table 5. The mean and standard deviation (SD) values of the likelihood of occurrence and impact for the 15 risk events were also calculated (in a scale from 1 to 5) and are shown in Table 6.

**Table 5.** RII values for the likelihood of occurrence and impact of risk events.

Risk Event	Likelihood		Impact		Severity		Rank
	RII	Level	RII	Level			
Late delivery of materials	69.2%	LIK	68.8%	MAJ	47.7%	HIG	5
Scope change (additions/deletion)	74.2%	ALC	69.2%	MAJ	51.3%	EXT	2
Efficiency, late arrival, and downtime of equipment	53.5%	UNL	71.5%	CAT	38.2%	MED	11
Rework due to design errors and conflicts in contract documents	57.7%	POS	66.5%	MAJ	38.4%	MED	10
Errors in the estimation of quantities and costs	68.8%	LIK	70.4%	CAT	48.5%	HIG	4
Limited funds	48.5%	RAR	64.6%	MOD	31.3%	LOW	13
Quality problems (poor quality and failure to meet specifications)	62.7%	POS	61.9%	MOD	38.8%	MED	9
Availability of skilled resources	58.8%	POS	68.8%	MAJ	40.5%	HIG	8
Complex design	53.1%	UNL	71.9%	CAT	38.1%	MED	12
Delay in the approval of materials and shop drawings	71.9%	ALC	63.5%	MOD	45.6%	HIG	6
Poor coordination during design and construction	70.4%	ALC	60.8%	MOD	42.8%	HIG	7
Poorly defined scope and inadequate design details	70.8%	ALC	72.7%	CAT	51.4%	EXT	1
Weather conditions	46.5%	RAR	48.5%	INS	22.6%	NEG	15
Errors in the estimation of task durations	74.6%	ALC	66.5%	MAJ	49.6%	HIG	3
Different site conditions	48.5%	RAR	53.1%	MIN	25.7%	LOW	14

**Table 6.** Mean and standard deviation values for the likelihood of occurrence, impact, and severity of risk events.

Risk Event	Likelihood		Impact		Severity	
	Mean	SD	Mean	SD	Mean	SD
Late delivery of materials	3.46	2.43	3.44	2.46	2.38	1.19
Scope change (additions/deletion)	3.71	3.25	3.46	2.37	2.56	1.54
Efficiency, late arrival, and downtime of equipment	2.67	1.50	3.58	2.76	1.91	0.83
Rework due to design errors and conflicts in contract documents	2.88	1.28	3.33	2.22	1.92	0.57
Errors in the estimation of quantities and costs	3.44	2.56	3.52	2.54	2.42	1.30
Limited funds	2.42	1.01	3.23	2.01	1.57	0.41
Quality problems (poor quality and failure to meet specifications)	3.13	1.78	3.10	1.79	1.94	0.64
Availability of skilled resources	2.94	1.57	3.44	2.47	2.03	0.77
Complex design	2.65	1.36	3.60	2.74	1.91	0.75
Delay in the approval of materials and shop drawings	3.60	2.85	3.17	1.89	2.28	1.08

Table 6. Cont.

Risk Event	Likelihood		Impact		Severity	
	Mean	SD	Mean	SD	Mean	SD
Poor coordination during design and construction	3.52	2.54	3.04	1.73	2.14	0.88
Poorly defined scope and inadequate design details	3.54	2.74	3.63	2.93	2.57	1.61
Weather conditions	2.33	1.37	2.42	1.34	1.13	0.37
Errors in the estimation of task durations	3.73	3.26	3.33	2.24	2.48	1.46
Different site conditions	2.42	1.54	2.65	1.31	1.29	0.40

## 6. Results and Discussion

As shown in Tables 5 and 6, the likelihood of occurrence of the “errors in the estimation of task durations” is the most probable risk event to happen among the 15 identified risk events with an *RII* of 74.6% (mean = 3.73 and SD = 3.26) and, therefore, is ranked first. The “scope change (additions/deletion)” is ranked second with an *RII* of 74.2% (mean = 3.71 and SD = 3.25), while the “weather conditions” risk event is the least probable to happen with an *RII* of 46.5% (mean = 2.33 and SD = 1.37). On the other hand, the impact of the “poorly defined scope and inadequate design details” risk event is ranked first with an *RII* of 72.7% (mean = 3.63 and SD = 2.93), followed by the “complex design” risk event with an *RII* of 71.9% (mean = 3.60 and SD = 2.74). The “weather conditions” risk event is ranked last in terms of its impact with an *RII* of 48.5% (mean = 2.42 and SD = 1.34). The severity of each risk event was then calculated using the following equation:

$$\text{Severity (S)} = \text{Frequency of Occurrence (F)} \times \text{Impact (I)} \quad (2)$$

The mean and standard deviation (SD) values of the severity of risk events were calculated and are given in Table 7. The calculated risk severity is maximum for the “poorly defined scope and inadequate design details” risk event with a severity level of  $70.8\% \times 72.7\% = 51.4\%$  (mean = 2.57 and SD = 1.61), followed by the “scope change (additions/deletion)” risk event with a severity level of 51.3% (mean = 2.56 and SD = 1.54). The “weather conditions” risk event came last (severity level = 22.6%, mean = 1.13, and SD = 0.37). The rank of the 15 risk events is given in the last column of Table 6.

Table 7. Levels of severity of risk events.

Severity	Level of Risk Severity
Negligible (NEG)	<4%
Low (LOW)	≥4% to <16%
Medium (MED)	≥16% to <40%
High (HIG)	≥40% to <60%
Extreme (EXT)	≥60%

## 7. Development of a Generic Framework for Managing risks

The data received from the responses of construction experts were analyzed and a spreadsheet framework was then developed using a Visual Basic for Applications (VBA) event-driven programming language to help construction practitioners manage schedule and cost risk events of their construction projects in an effective and dynamic manner. The developed framework is composed of four main modules: (1) the risk severity matrix generation module; (2) the project scheduling module; (3) the quantitative risk analysis module; and (4) the risk response module. The developments made for each module are summarized as follows:

**The risk severity matrix generation module:** this module was developed to generate the risk severity matrix using the following structured steps:

1. The number of responses received for each of the likelihood of occurrence ranges (RAR, UNL, POS, LIK, and ALC) and impact ranges (INS, MIN, MOD, MAJ, and CAT) are entered for each of the 15 risk events. Based on the entered values, the framework calculates the *RII* values for the likelihood of occurrence and impact of each risk event using Equation (1).
2. Using Equation (2), the framework calculates the severity level of each risk event based on the *RII* values calculated in item 1 above.
3. The *RII* range for the levels of occurrence and impact of risk events given in Table 1 are then entered and, using this data, the framework calculates a generic range of severity levels using Equation (2). The *RII* ranges given in Table 1 for the levels of occurrence and impact of risk events form two 5 × 5 severity risk matrices for the minimum and maximum values of the *RII* ranges. Figure 2 shows the data tables used to calculate the minimum and maximum value range of the levels of severity of risk events. The table on the left side of Figure 2 shows the percentage range of the probability of occurrence and impact of risks, while the two tables on the right side automatically calculate the minimum and maximum values of risk severity.

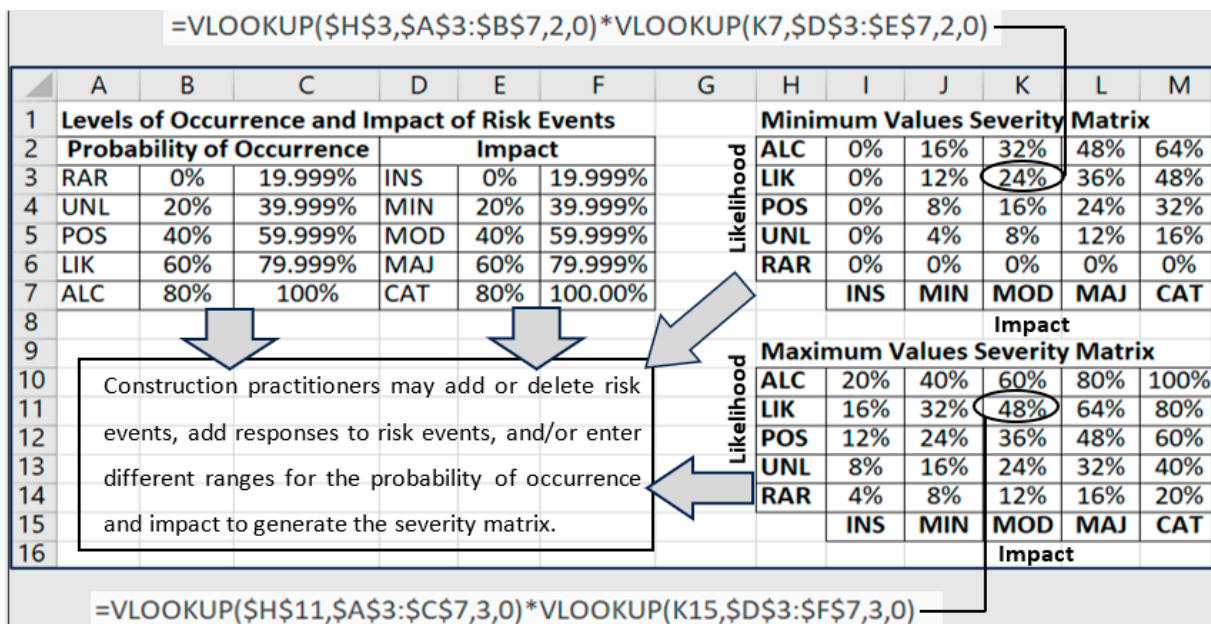


Figure 2. The minimum and maximum values of risk severity.

Since projects evolve over time and risks may emerge or change throughout the project lifecycle, it is important to update these risk matrices periodically considering the dynamic nature of risks during the evolution of construction projects. Therefore, the framework allows construction practitioners to update, add, and delete risk events, as deemed necessary. Also, if a construction practitioner decides to select a range of *RII* percentages for the levels of occurrence and impact different from the ones given in Table 1, the minimum and maximum values of risk severity will be updated accordingly. Using VBA, the framework is programmed to allow construction practitioners to make these changes for their projects, if needed.

1. The two tables at the right side of Figure 2 calculate the minimum and maximum values of risk severity using the “Vlookup” function of the Microsoft 365 Excel. For example, the minimum value of the severity of a particular risk event with a “Likely (LIK)” probability of occurrence and a “Moderate (MOD)” impact of will

be  $60\% \times 40\% = 24\%$ , while the maximum value will be  $80\% \times 60\% = 48\%$ . The calculated minimum and maximum values of risk severity in the two tables, shown in the right side of Figure 2, automatically generate a risk severity matrix, representing a range for each level of risk severity in the matrix array. Table 7 shows the range for each level of risk severity, while Table 8 shows the risk severity matrix generated from the calculated range of each level of risk severity.

**Table 8.** Risk severity matrix.

Likelihood	ALC	MED	MED	HIG	EXT	EXT
	LIK	LOW	MED	HIG	EXT	EXT
	POS	LOW	MED	MED	HIG	HIG
	UNL	LOW	LOW	MED	MED	MED
	RAR	NEG	LOW	LOW	LOW	MED
	INS	MIN	MOD	MAJ	CAT	
				<b>Impact</b>		

The severity of a risk event is considered negligible (NEG) if the value of the calculated severity is between 0 and 4% and the severity level increases as this percentage increases. The generated 25-array risk severity matrix of Table 7 is composed of 1 negligible (NEG), 7 low (LOW), 9 medium (MED), 4 high (HIG), and 4 extreme (EXT) levels of risk severity. Tables 7 and 8 are used in this study for the quantitative assessment of the severity of schedule and cost risk events of construction projects.

**The project scheduling module:** this module is used to schedule the project's activities and determine its duration and identify critical activities. The module was developed as follows:

1. For a given set of activities in a project and their corresponding three "PERT" times (optimistic ( $o$ ), most likely ( $m$ ), and pessimistic ( $p$ )), the expected time ( $t_e = \frac{o+4m+p}{6}$ ), standard deviation ( $\sigma = \frac{p-o}{6}$ ), and variance ( $v = \sigma^2$ ) are calculated for each activity.
2. Microsoft Project scheduling software then reads the expected times ( $t_e$ ) of activities from Excel using VBA in order to schedule the project and identify critical activities. Excel then reads the project's expected time ( $T_E$ ) from Microsoft Project software and calculates the project's standard deviation ( $\sigma_{TE}$ ) using the critical activities identified by Microsoft Project software.

**The quantitative risk analysis module:** this module uses the data received from Microsoft Project software to estimate the monetary effect of schedule and cost risks. The development of this module included the following:

1. Using the project's calculated  $T_E$  and  $\sigma_{TE}$ , this module calculates the probability ( $P_T$ ) of finishing the project in its baseline duration stipulated in the contract ( $T_S$ ).  $P_T$  is calculated using Excel function " $=\text{NORMDIST}(x, \text{mean}, \text{standard\_dev}, \text{cumulative})$ ", where " $x$ " is baseline duration of the project ( $T_S$ ), " $\text{mean}$ " is the " $T_E$ " value obtained from Microsoft Project software using the critical path method (CPM) technique, and " $\text{standard\_dev}$ " is the calculated " $\sigma_{TE}$ " for critical activities of the project. The probability of risk ( $PR_T$ ) for finishing the project in its " $T_S$ " duration is then calculated as follows:

$$PR_T = 1 - P_T \quad (3)$$

2. Since a delay in finishing a construction project on its scheduled baseline time ( $T_S$ ) results in liquidated damages (delay penalty) to be paid by contractors for each day

of delay as stipulated in the contract, the monetary impact resulting from the delay is calculated as follows:

$$\text{Impact of the delay} = \text{the overall delay (in days)} \times \text{the liquidated damages (delay penalty) stipulated in the contract} \quad (4)$$

Finally, the severity of the risk associated with the project's schedule ( $SR_T$ ) is calculated as follows:

$$SR_T = \text{monetary impact resulting from the delay} \times PR_T \quad (5)$$

3. The procedure of quantifying the risk associated with the project's cost (bid price) is similar to that used for the project's schedule, where a variation in costs for each activity is assigned (optimistic, most likely, and pessimistic) to establish the probability distribution corresponding to the cost of each activity in a project. The "PERT" technique is then used to calculate the expected project's cost ( $C_E$ ) and the standard deviation of the expected project's cost ( $\sigma_{CE}$ ). The module provides an alternative way to quantify the risk associated with the project's cost (bid price) using the "Pareto Principle" in order to select the tasks with significant cost impact for further analysis. The Pareto Principle assumes that 80% of the effect (consequences) comes from 20% of the causes (Le et al., 2022) [55]. This principle is also called the 80/20 rule or the 'law of the vital few.' In cost estimation, the Pareto Principle suggests that around 20% of items are responsible for around 80% of the total project cost. Following this rule, this module of the suggested framework selects the most expensive 20% of tasks and the accumulated costs of these tasks are considered to account for around 80% of the total project cost and used as the expected cost of the selected activities in the project ( $C_E$ ).
4. Once the costs are identified and the expected project's cost ( $C_E$ ) and standard deviation of the expected project's cost ( $\sigma_{CE}$ ) are calculated, the procedure of quantifying the risk associated with the project's cost is similar to that used for the project's schedule. This module then calculates the probability ( $P_C$ ) of meeting the planned baseline bid price of the project ( $C_S$ ) using Excel function " $=\text{NORMDIST}(x, \text{mean}, \text{standard\_dev}, \text{cumulative})$ ", where " $x$ " is the planned baseline bid price of the project ( $C_S$ ), " $\text{mean}$ " is the expected price value of the project " $C_E$ " calculated from the "PERT" three cost values (optimistic, most likely and pessimistic), and " $\text{standard\_dev}$ " is the calculated " $\sigma_{CE}$ " for the project. The probability of risk ( $PR_C$ ) to meet the project's baseline bid price is then calculated as follows:

$$PR_C = 1 - P_C \quad (6)$$

5. The EV technique is then used to measure the progress of the project's schedule at any point of time during construction using the schedule performance index ( $SPI = \frac{BCWP}{BCWS}$ ) or the schedule variance ( $SV = BCWP - BCWS$ ). The EV technique is also used to measure the project's cost progress during construction using the cost performance index ( $CPI = \frac{BCWP}{ACWP}$ ) or the cost variance ( $CV = BCWP - ACWP$ ), where:
  1.  $BCWS$  is the budgeted cost of work scheduled ( $C_S$ ); this measures what is planned in terms of the budget cost of the work that should take place according to the baseline schedule of the work.
  2.  $BCWP$  is the budgeted cost of work performed (also called the earned value); this measures what is done in terms of budget cost of work that has actually been accomplished (completed) to date.
  3.  $ACWP$  is the actual cost of work performed; this measures what is paid in terms of the actual cost of work that has actually been accomplished (completed) to date.

A value of the " $SPI$ " greater than one (or  $SV > 0$ ) indicates a schedule advantage while a value of " $CPI$ " greater than one (or  $CV > 0$ ) indicates cost savings. The  $CPI$  and  $CV$  are

then used to estimate the project's cost at completion ( $EAC$ ) at any point of time during construction using any of the following equations:

$$EAC = BCWS_{(\text{at completion})} - CV_{(\text{at present})} \quad (7)$$

$$EAC = BCWS_{(\text{at completion})} / CPI_{(\text{at present})} \quad (8)$$

- 6 Once the estimate at completion ( $EAC$ ) is calculated for a project at any point of time during construction, the monetary impact resulting from the effect of the current  $CV$  or  $CPI$  on the estimate at completion ( $EAC$ ) is then calculated as follows:

$$\text{The impact of the } EAC = EAC \text{ (calculated from equations 6 or 7)} \times (\text{the project's pessimistic price} - C_5) \quad (9)$$

Finally, the severity of the risk associated with the project's bid price (cost) is calculated as follows:

$$SR_C = \text{the impact of the } EAC \times PR_C \quad (10)$$

**The risk response module:** this module suggests responses to risks associated with the project's schedule and cost. Depending on the risk event that may result in a delay or a cost overrun, the framework will suggest a set of responses related to this risk event. The following are some suggested responses for each of the 15 most important schedule and cost risk events considered in this study. As shown in the "Risk Response Module" of Figure 3, project managers may suggest more responses to current risk events and add responses to the newly added risk events.

1. Late delivery of materials:
  - Diversify suppliers to have alternative material sources.
  - Have a contingency to allow for delays and increases in material prices.
  - Hire well-experienced procurement staff.
  - Use domestic material suppliers whenever possible.
  - Have an effective material supply chain management.
  - Regularly evaluate the performance of material suppliers.
  - Plan the delivery of materials ahead of time, particularly for critical tasks.
  - Make sure to have contracts with material suppliers that include delivery dates and clearly defined penalties.
  - Define lead times for material delivery in the contracts with suppliers and track long-lead materials.
2. Scope change (additions/deletion):
  - Ensure clear project scope and specifications.
  - Make a constructability review.
  - Promote effective communication among all parties and ensure proper coordination during design to avoid redesign and added cost and delays.
  - Have an established change order process and include a provision in the contract about change order procedures and rights of parties.
  - Have an established quality control process.
  - Obtain written approvals for all change orders.
  - Check the impact of change order on the project's schedule.
  - Select a type of contract that provides flexibility for changes.
3. Efficiency, late arrival, and downtime of equipment:
  - Hire well-experienced procurement staff.
  - Diversify equipment suppliers to have alternative sources.
  - Use domestic equipment suppliers whenever possible.
  - Have an effective equipment supply chain management.
  - Regularly evaluate the performance of equipment suppliers.

- Plan the delivery of equipment ahead of time, particularly for critical tasks.
  - Make sure to have contracts with equipment suppliers that include delivery dates and clearly defined penalties.
  - Have a contingency plan in case the equipment is not delivered on time.
  - Schedule equipment downtime, create a maintenance schedule, and keep maintenance and repair records.
  - Assign a qualified maintenance team.
  - Provide periodical lubrication, oil changes, and filter changes, etc.
  - List all routine and preventative maintenance requirements.
  - Create backup plans in case of equipment delay/failure.
  - Organize the site properly for maximum productivity.
  - Check that equipment operators are qualified and have good training to operate and maintain equipment.
  - Use equipment efficiently and use an optimum fleet of equipment.
4. Rework due to design errors and conflicts in contract documents:
- Hire an experienced design team.
  - Assign a coordinator during the design and construction stages.
  - Promote effective communication among all parties.
  - Allocate enough time for design.
  - Review the various components of the design for errors, mistakes, discrepancies, and mismatches during the design stages to avoid costly rework, delays, and disputes, and ensure that the project meets the expectations of the client.
  - Have professional liability insurance to transfer the risk of major design errors and mistakes to a third party.
  - Review cross-referencing in drawings and other contract documents to avoid discrepancies and mismatches among the various design drawings and other contract documents.
5. Errors in the estimation of quantities and costs:
- Have a clear and accurate scope definition to avoid underestimating or overestimating the project's cost, duration, and quality.
  - Allocate enough time for quantity takeoff and cost estimation.
  - Use reliable software for quantity takeoff instead of manual practices to improve accuracy.
  - Use consistent units and formats, cross-check your calculations, and update your data regularly to improve the reliability of the quantity takeoff.
  - Study current market trends and analyze your competitors.
  - Negotiate with your suppliers.
  - Track your overhead costs and evaluate your risks and opportunities.
  - Have a contingency plan in place to cover unexpected costs that may arise from errors and mistakes in quantities and cost estimation.
  - Allocate enough time for quantity takeoff and cost estimation.
  - Make periodical reviews and checks on quantities and unit prices.
  - Select the right type of contract.
6. Limited funds:
- Ensure an effective cost control system from the beginning of the project.
  - Perform a value engineering exercise to reduce costs without affecting the functions or quality of the project.
  - Perform time–cost tradeoff analysis (activities crashing). This exercise normally results in saving time and cost.
  - Ensure accurate cost estimation.
  - Manage the cash flow properly during the different stages of the project.
  - Explore adaptive budgeting techniques to mitigate cost overruns.

- Have clear communication among project stakeholders including subcontractors and suppliers. This is essential for effective fund management.
  - Make payment arrangements with subcontractors and material suppliers. Agreed delayed payments help contractors improve their funds for projects.
  - Have professional liability insurance to mitigate unexpected costs resulting from negligence or mistakes made by project professionals.
7. Quality problems (poor quality and failure to meet specifications):
- Identify, assess, and prepare responses for quality risks early during the project's life cycle and implement a response plan.
  - Have clear procedures and a control system in place for quality control and implement it carefully and effectively by monitoring and controlling your quality performance.
  - Assign a team to supervise the work on site.
  - Review and improve your quality system.
  - Make sure to have quality and clear design drawings and specifications with minimum or no omissions discrepancies, errors, mistakes, and mismatches.
  - Avoid using low-quality material to meet a budget.
  - Use experienced engineers and skilled labor.
  - Avoid complex designs.
  - Avoid frequent and last-minute changes. These can compromise the quality of the final project.
8. Availability of skilled resources:
- Prepare histograms/profiles for all resources to identify the daily requirements of skilled resources during construction.
  - Increase and incentivize training programs for labor.
  - Create a training outreach program through an industry association.
  - Adopt new equipment and technologies that decrease labor needs.
  - Invest in automation whenever possible to reduce the reliance on labor.
  - Implement project management software to decrease the time it takes to perform a host of activities and thereby make your crew more productive and decrease labor needs.
  - Improve safety precautions on site to attract skilled labor.
  - Expand your efforts to recruit skilled labor and target the young generation.
  - Provide attractive and competitive salaries.
  - Subcontract to qualified contractors.
9. Complex design:
- Get experienced engineers heavily involved early during the design stage in an attempt to avoid complex designs.
  - Educate designers about the risks associated with complex designs and how these risks contribute significantly to the delays and cost overruns of construction projects.
  - Perform an early assignment to recognize and identify undesirable risk events related to complex designs.
  - Have a contingency plan to deal with risks resulting from complex designs.
10. Delay in the approval of materials and shop drawings:
- Have a pre-defined schedule of submittals for all materials and shop drawings prepared before the commencement of construction.
  - Submit materials and shop drawings ahead of time to avoid delays in the approval.
  - Document all submittals and follow up on the approval status of materials and shop drawings on a regular basis.
  - Give priority to critical tasks for material and shop drawing submittals.

- Claim time extension and compensation resulting from the failure of the client to approve materials and shop drawings within the time stipulated in the contract.
11. Poor coordination during design and construction:
    - Assign a coordinator during the design and construction stages.
    - Establish effective communication channels and promote them among parties.
    - Encourage regular meetings and updates among all project stakeholders.
    - Conduct periodic coordination meetings during design and construction.
    - Review cross-referencing in drawings and other contract documents to avoid discrepancies and mismatches among the drawings and other contract documents.
  12. Poorly defined scope and inadequate design details:
    - Define the scope accurately when you have enough information about the project and do not define it too early with little information.
    - Ensure the schedule and resource plan is centered on the defined deliverables.
    - Measure performance against the project's baseline.
    - Involve stakeholders in the project work and have their input to define and review the client requirements.
    - Allocate sufficient time for design and the production of design documents.
    - Clearly define the project's constraints in terms of time, budget, and resources.
    - Evaluate scope, schedule impact, and resource requirements before any new activities are included within the schedule.
    - Use clear language and terms to describe the project's scope and avoid vague statements.
    - Check the completeness of contract documents.
    - Review contract documents to avoid omissions, discrepancies, errors, mistakes, and mismatches.
  13. Weather conditions:
    - Be proactive and monitor upcoming weather reports.
    - Use weather risk management software to manage extreme weather conditions.
    - Install weather instruments at the project site to provide weather forecasting data. This includes data about wind, rain, snow, ice, temperature, etc.
    - Use historical weather records for long-term planning.
    - Make contingency plans for extreme weather events.
    - Use safety personal protective equipment, such as hard hats, masks, goggles, and heavy-duty gloves when working outdoors in harsh weather conditions.
    - Foster good communication on site among workers, vendors, and other stakeholders during harsh weather conditions to ensure that everyone is aware of the risks when bad weather strikes.
    - Use good-quality construction equipment that is robust enough to withstand extreme weather conditions.
    - Train construction workers on the potential risks of working outdoors during extreme weather, including common hazards such as falling debris, slippery surfaces, electrical accidents, etc. Training includes appropriate safety precautions to be taken as a protective measure against these risks.
    - Schedule activities that require the use of cranes on clear days.
    - Store materials on pallets and off the ground to protect them from standing water or flood situations, thereby limiting potential damage.
    - Begin earthwork and trenching activities when the ground is dry and cover the trench before it rains.
    - Install the exterior façade and windows as early as possible to protect the interior work.
    - Start critical activities as early as possible and on clear days.

14. Errors in the estimation of task durations:
  - Clearly define the scope of work, including specifications, drawings, resource requirements (materials, labor, and equipment), and contingencies.
  - Perform accurate quantity takeoff. Task durations are highly dependent upon the accurate estimation of task quantities.
  - Estimate the number and productivity of crews needed for each task.
  - Adjust durations for weather conditions and productivity factors.
  - Review the accuracy of estimated task durations in order to identify the root causes of the task duration errors and the lessons learned from these mistakes. These lessons learned along with the best practices and recommendations for better estimates should be well documented and shared for future improvements.
  - Monitor and control time estimates to track the actual times of activities and the project as a whole against the estimated baseline and measure the variances.
  - Report the schedule progress of the individual activities and the project using the earned value technique, “schedule performance index”, or “schedule variance” and to the stakeholders regularly and honestly and implement corrective actions if the variances are significant or at unacceptable levels.
15. Different site conditions:
  - Carefully review all contract documents, including the project’s geotechnical investigation report.
  - Conduct your own geotechnical investigation report to check the site’s underground conditions.
  - Conduct site visits before submitting bids to assess any additional risks and inspect its accessibility, weather conditions, availability of services, bylaws, etc.
  - Promptly report any unforeseen site conditions encountered.
  - Include a clause in the contract about “latent conditions” to transfer the risk of differing site conditions to the client. The latent conditions clause generally states that if the contractor encounters a different condition during the execution of the work, the client will compensate the contractor for the resulting cost and/or time.
  - Ask for as-built drawings of underground utilities and structures. These include existing cables, pipes, and other utilities on or near the site of the project.

Figure 3 illustrates the main components of the developed risk management framework.

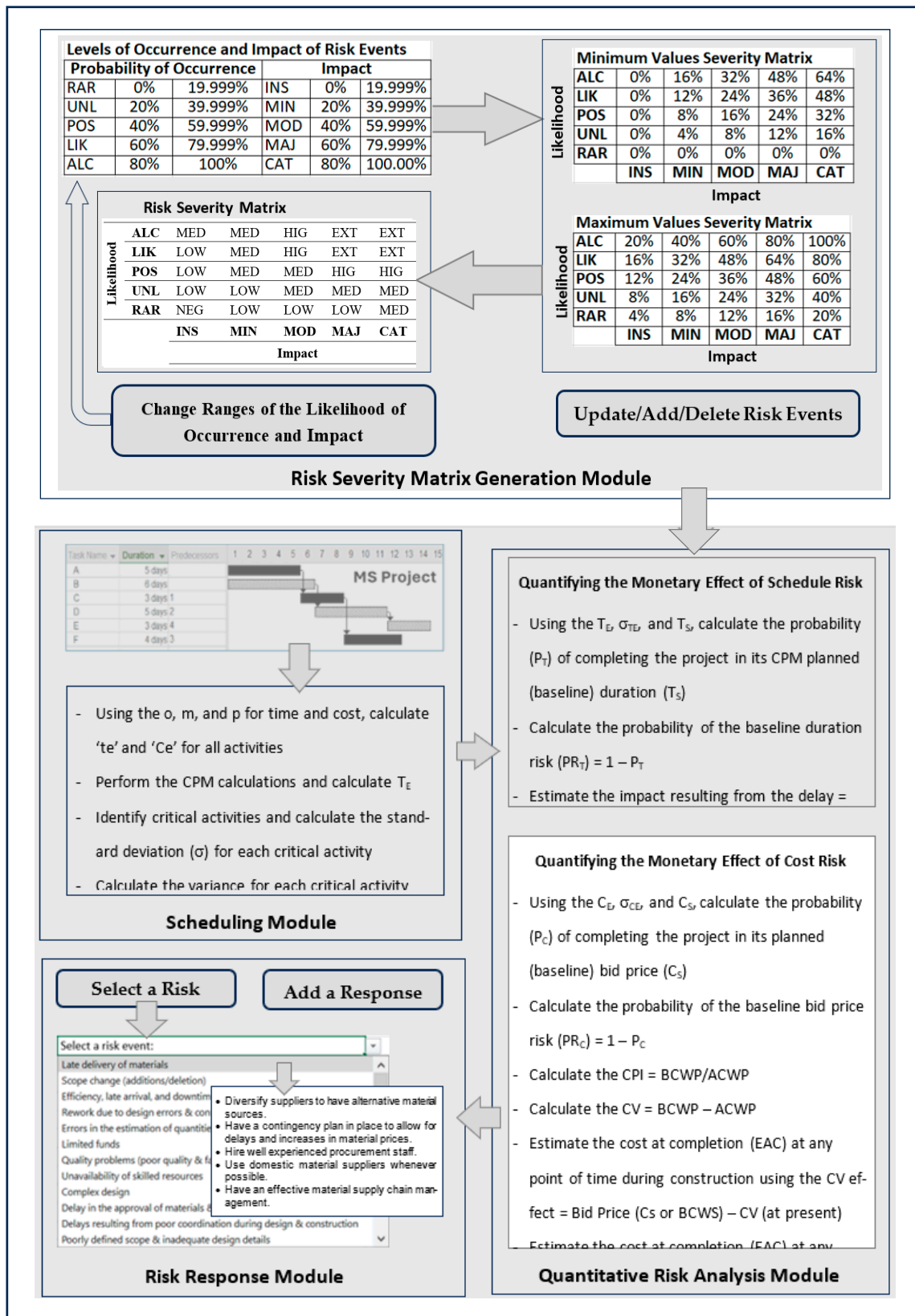


Figure 3. The main components of the developed risk management framework.

## 8. Example of Using the Developed Framework

A hypothetical example is presented in this section to illustrate the utilization of the framework proposed in this study and the use of the “PERT” and the earned value technique to assess the qualitative severity of schedule and cost risks and mitigate their impact. The optimistic, most likely, and pessimistic times (in days) and costs (in USD) of a 21-task small project shown in Table 9 are considered in this example.

**Table 9.** PERT times and costs of the tasks of the example.

Task	Time (Days)					Cost (\$)				
	<i>O</i>	<i>M</i>	<i>P</i>	$t_e$	$\sigma$	<i>O</i>	<i>M</i>	<i>P</i>	$C_e$	$\sigma$
1–2	2	6	9	5.83	1.17	120,000	150,000	190,000	151,667	11,667
2–3	1	4	8	4.17	1.17	50,000	75,000	95,000	74,167	7500
2–4	8	10	13	10.17	0.83	135,000	150,000	170,000	150,833	5833
3–7	3	6	8	5.83	0.83	70,000	85,000	100,000	85,000	5000
3–9	7	9	12	9.17	0.83	150,000	170,000	195,000	170,833	7500
4–5	6	9	13	9.17	1.17	240,000	250,000	270,000	251,667	5000
4–8	5	7	10	7.17	0.83	190,000	210,000	240,000	211,667	8333
4–7	Dummy									
5–6	4	6	8	6.00	0.67	135,000	150,000	170,000	150,833	5833
5–8	Dummy									
6–10	2	3	5	3.17	0.50	450,000	550,000	600,000	541,667	25,000
7–8	12	14	17	14.17	0.83	1,240,000	1,280,000	1,330,000	1,281,667	15,000
7–9	5	8	12	8.17	1.17	740,000	900,000	1,100,000	906,667	60,000
7–15	7	9	12	9.17	0.83	120,000	140,000	170,000	141,667	8333
8–11	7	10	12	9.83	0.83	340,000	360,000	390,000	361,667	8333
9–12	9	11	14	11.17	0.83	2,250,000	2,400,000	2,700,000	2,425,000	75,000
10–11	3	5	8	5.17	0.83	730,000	750,000	900,000	771,667	28,333
10–13	5	7	11	7.33	1.00	40,000	55,000	65,000	54,167	4167
11–14	5	8	10	7.83	0.83	4,500,000	5,000,000	7,000,000	5,250,000	416,667
12–15	8	10	13	10.17	0.83	95,000	100,000	110,000	100,833	2500
13–14	3	5	8	5.17	0.83	7,000,000	8,000,000	10,000,000	8,166,667	500,000
14–15	3	5	8	5.17	0.83	10,500,000	11,000,000	12,000,000	11,083,333	250,000
15–16	6	8	11	8.17	0.83	4,200,000	4,500,000	5,400,000	4,600,000	200,000

The expected time ( $t_e$ ) and expected cost ( $C_e$ ) are first calculated for all tasks using the “PERT” technique. The list of tasks, their expected times ( $t_e$ ), and their predecessors are then read by Microsoft Project scheduling software to schedule the project and calculate its expected completion time ( $T_E$ ) for the critical path. Table 10 shows the list of expected risk events associated with some of the tasks of the example along with the expected resulting delays. The framework will then identify the severity of each of these risk events, as shown in Table 10.

The “ $T_E$ ” duration of the critical path was found to be 61.17 days and the duration of the next longest path in the project is 60.18 days. The durations of other paths are much smaller than these two paths. The baseline duration of the project as required by the client is 63 days and, due to the urgency of completing the project on this duration, the liquidated damages (delay penalty) clause of the conditions of the contract states that the contractor should pay \$20,000 per day of delay caused by the contractor to compensate the owner for the damages resulting from the delay. After identifying the severity of risk events (last column of Table 10) and the delays resulting from these events, it was

found that the durations of the two longest paths are 68.17 and 67.18 days. Since the critical path did not change, the total delay resulting from the tasks associated with the critical path tasks “2–4”, “8–11”, “14–15”, and “15–16” are 1, 1, 1, and 4 days, respectively, resulting in a total estimated project delay of 7 days. A total of 5 days of delay are resulting from the “late delivery of materials” risk event, while the “availability of skilled resources” and “weather conditions” risk events resulted in 1 day of delay each. The suggested framework then calculates the impact of these delays on the project’s duration ( $=5 \times 0.477 + 1 \times 0.405 + 1 \times 0.226 = 3.016$  days). The monetary severity of the delay resulting from the risk events of the critical path considering the penalty to be paid by the contractor is calculated ( $=\$20,000 \times 3.016 = \$60,320$ ). Using the “PERT” technique, the suggested framework calculates the probability of completing the project in the scheduled duration (63 days) as 78.22%, considering the calculated 2.35 day standard deviation of critical activities ( $\sigma_{TE}$ ), where  $\sigma_{TE}$  is the square root of the summation of time variances of critical tasks. The probability of risk for finishing the project in its “ $T_S$ ” duration (63 days) is then calculated using Equation (3) ( $=100\% - 78.22\% = 21.78\%$ ). Using Equation (2) and considering the calculated probability of schedule risk, the framework calculates the monetary severity associated with the schedule risk as follows: monetary severity of schedule risk =  $0.2178 \times (80-63) \times \$20,000 = \$74,040$ , where 63 is “ $T_S$ ” and 80 in the pessimistic duration of the critical path in days. The total amount associated with the schedule risk is finally calculated by adding the risk amount resulting from the risk events to the monetary severity of schedule risk =  $\$60,320 + \$74,040 = \$134,360$ . This amount is used for mitigating risks associated with the project’s schedule by adding it to the project’s bid price.

**Table 10.** Expected risk events associated with the tasks of the example.

Task	Delay (Days)	Expected Risk Event	Severity
2–3	2	Scope change (additions)	EXT (51.4%)
2–4 *	1	Late delivery of materials	HIG (47.7%)
3–9	2	Availability of skilled resources	HIG (40.5%)
5–6	1	Errors in the estimation of task durations	HIG (49.6%)
7–9	3	Late delivery of materials	HIG (47.7%)
7–15	1	Weather conditions	NEG (22.6%)
8–11 *	1	Availability of skilled resources	HIG (40.5%)
9–12	3	Complex design	MED (38.2%)
14–15 *	1	Weather conditions	NEG (22.6%)
15–16 *	4	Late delivery of materials	HIG (47.7%)

\* Critical Tasks.

Finally, the monetary severity of the risk associated with the project’s baseline bid price (budget) is calculated for this example. Using the developed framework, the schedule and cost progress can be calculated for this example at any point of time using the earned value (EV) technique. Let us first assume that the contractor decided to submit a bid ( $C_S$ ) of \$37,500,000 for the project presented in this example. Given the cost data of Table 9 and using the “PERT” technique, the proposed framework calculates the expected project’s price ( $C_E = \$36,931,667$ ) and the of the standard deviation of the cost ( $\sigma_{CE} = \$733,204$ ), where  $\sigma_{CE}$  is the square root of the summation of cost variances of all tasks. The cost performance index ( $CPI = BCWP/ACWP$ ), cost variance ( $CV = BCWP - ACWP$ ), and estimated cost at completion ( $EAC = BCWS_{(at\ completion)}/CPI_{(at\ present)}$ ) are then calculated at any point of time during construction. Two weeks after the start of the project, the bar chart data of Microsoft Project are used to calculate the project’s “SPI” and “CPI” (0.94 and 0.91, respectively), indicating that the project is behind schedule and incurring cost overrun. Using the “PERT” technique and considering the calculated “ $C_E$ ” and “ $\sigma_{CE}$ ” values of \$36,931,667

and \$733,204, respectively, the probability of the project's bid price ( $C_S$ ) being \$37,500,000 is found to be 86.7%. The *EAC* value is then calculated using Equation (8) as follows:  $EAC = \$37,500,000/0.91 = \$41,208,791$ . In this example, the calculated "PERT" pessimistic price of the project is \$43,195,000. The severity of the project's bid price risk is calculated and added to the calculated *EAC* to estimate the final *EAC* of the project considering the risk associated with the project's bid price. These calculations are performed as follows:

- The severity of the project's bid price risk = (the estimated pessimistic price of the project—the project's bid price (CS))  $\times$  (1—the probability of completing the project in its bid price value (CS)) =  $(\$43,195,000 - \$37,500,000) \times (1 - 0.7809) = \$1,247,775$ , where 0.7809 (or 78.09%) is the probability of completing the project in its bid price value.
- The estimated *EAC* of the project considering the risk associated with the project's bid price =  $\$41,208,791 + \$1,247,775 = \$42,456,566$ . The estimated *EAC* of \$42,456,566 is compared to the \$37,500,000 contractor's original bid price and is used to mitigate the risk associated with the project's bid price.

Considering the risk events associated with this example and listed in Table 10, the proposed framework will suggest possible risk responses to these risk events. The presented example demonstrates the effectiveness of the proposed risk management framework in estimating the risks associated with the project's schedule and bid price and suggests possible responses to risk events. The risk responses and mitigation strategies suggested in this study can help project managers effectively manage schedule and cost risks associated with their projects and mitigate their effect and severity.

### 9. Risk Mitigation Strategies Suggested by Construction Experts

Project managers must develop a plan to effectively mitigate the effect of identified risks on the project's schedule and cost and bring these risks to an acceptable level. This includes the development of preventive measures to reduce the probability of occurrence and mitigative actions to minimize impact. It also requires the adjustment of some project requirements or constraints to eliminate or reduce identified risks. This adjustment could be accommodated by a change in funding, schedule, or technical requirements. Providing adequate resource allocation and clearly defined responsibilities are crucial for successful risk management. The following generic guidelines are suggested by the survey respondents to mitigate high impact risks in construction projects:

1. Prepare a detailed risk management plan and implement it carefully.
2. Obtain firm commitment from the organization for funding and staff.
3. Seek feedback from construction experts to determine the likelihood of occurrence and impact of each risk event.
4. Replan the work to avoid/remove some specific serious risks. It is important to note that avoiding a risk means taking another course of action so that the risk does not arise in new circumstances.
5. Avoid overdesign and design using standard, modular, or well-understood methods. Do not reinvent the wheel.
6. Avoid complex designs.
7. Minimize safety and health issues that may result in a loss of project staff.
8. Avoid untried or unfamiliar technology whenever practical and look for ways to achieve the required project specifications using tried-and-true technologies.
9. Clearly document all project deliverables.
10. Minimize changes.
11. Have an effective change management process.
12. Use a clear and consistent specification change control process.
13. Consider the impact of external and environmental problems.
14. Keep all contract documents current including drawings, specifications, bills of quantities, etc.
15. When you use outside services, use experienced and reputable suppliers that you trust and have used successfully in the past.

16. Ask for materials to be shipped early to avoid shipment delays.
17. Rigorously manage outsourcing and control the work performed by others by managing and communicating external dependencies proactively.
18. Detect and address problems in the project objective promptly.
19. Rigorously track project resource use (resource management).
20. Break large projects with large staff into smaller, parallel ones (e.g., work packages)
21. Break long projects into phases that produce measurable outputs with scheduled project reviews at the end of each phase.
22. Reduce the number of critical paths in a project to a minimum.
23. Modify the work to have fewer activity dependencies.
24. Schedule high-risk activities as early as possible.
25. Take advantage of using the line of balance (LOB) technique to schedule repetitive activities and linear projects.
26. Track progress with rigor and discipline, and report the status frequently.
27. Build teamwork and trust in the project team.
28. Avoid having the same staff members working on two successive or concurrent critical (or near-critical) activities.
29. Decompose lengthy activities further.
30. Reschedule work to provide better flexibility.
31. Use a proper and effective project organizational structure.
32. Obtain explicit availability commitments from all project staff and approvals from their managers and limit their commitments to other projects.
33. Modify plans to reduce the load on excessively committed staff.
34. Delegate risky work to experienced and successful problem solvers and use the best people available for the most critical activities.
35. Train team members to use more efficient or faster methods and do it early in the project.
36. Use mentoring to build teamwork and establish redundancy for critical skills.
37. Implement the necessary safety measures on site, as required by OSHA.
38. Upgrade or replace older equipment to make work more efficient.
39. Automate manual work when possible.
40. Gain access to experts to cover all skill areas not available in the project team.
41. Minimize dependence on a single individual or another resource for project work.
42. Establish contract terms with all suppliers and subcontractors that are consistent with project objectives.
43. Be aware that the exercise of risk avoidance might increase the severity of other risks, introduce new risks, or result in a lost opportunity.
44. Be aware that the exercise of risk reduction may result in residual risks.
45. Provide sufficient and reliable data for a reasonably accurate qualitative and quantitative analysis of risks, which helps in mitigating risks.
46. Establish a risk work breakdown structure and a risk register to track risks.
47. Provide enough time to correctly estimate activities' durations and quantities and pay attention to critical activities.
48. Pay attention to areas where costs may increase and include contingencies in the project's budget.
49. Monitor the project's schedule and cost and measure the project's performance with earned value management.
50. Have a clear and well-defined scope and avoid changing the scope of the project.
51. Make sure that materials are delivered on time and track material and shop drawing submittals to make sure that they are approved on time.
52. Assign a coordinator during the design and construction stages.
53. Do not finalize the project's budget until the plan and schedule are complete.
54. Transfer risks where the impact is primarily financial by reassigning accountability, responsibility, and authority to other stakeholders such as subcontractors and suppliers.

This also includes insurance against theft, injury, damage to property or equipment, and third-party liabilities. Other examples include the use of equipment warranties, bid bonds, performance bonds, payment guarantees, and delivery methods (e.g., joint ventures, public–private partnership, franchises, design–build, build–operate–transfer, etc.).

55. Continue the attempts to reduce risks iteratively until residual risks become as low as reasonably practicable.

## 10. Limitations and Recommendations for Future Work

While this study provides significant insights into managing schedule and cost risks in construction projects, it has some limitations that need to be addressed as future research work. These limitations are summarized as follows:

1. While a good percentage (58%) of the survey participants have more than 10 years of experience in the construction industry and their opinions might be reasonably true, the reliance on expert opinions may involve some subjectivity. This is because the feedback depends on the personal experiences of the respondents and may limit the generalization of the findings.
2. While the sample size used in this study (52 participants) is quite representative, it is recommended to have a larger size in order to obtain more accurate and reliable results.
3. Limiting the study to the construction industry in the UAE may not fully capture other risk factors, thus limiting the applicability of the results to the UAE. It is, therefore, recommended to expand the geographical scope of the research by including other countries. This will provide a comprehensive understanding of the risks associated with construction projects in a global context.
4. The study is limited to municipalities, contractors, and design offices. It is suggested to include other construction stakeholders such as developers, specialty contractors, suppliers and vendors, and other participants.
5. The study is limited to schedule and cost risk events. More research is needed considering other risk factors such as risks related to safety, political issues, the supply chain, etc.
6. While the use of the PERT and EV techniques is quite effective, it may not encompass all the complexities of modern construction projects, particularly those involving advanced technologies and innovative construction methods.
7. Future research should also explore the integration of emerging technologies such as building information modeling (BIM), artificial intelligence (AI), and machine learning (ML) in risk assessment and management, as these technologies have the potential of providing more precise and efficient risk analysis.
8. Using other qualitative methods, such as in-depth interviews and case studies, along with the quantitative techniques could offer a more holistic understanding of the risk management process related to construction projects.

## 11. Concluding Remarks

Construction projects are prone to delays and cost overruns due to their complexity and high levels of uncertainty, in addition to the enormous number of details and multiple participants involved. This nature of construction projects makes them risky and good candidates for failure, if risks are not managed effectively. The literature review identified 43 risk events related to schedule and cost construction activities. Several gaps were also identified from the review of previous research efforts and from the feedback received from construction experts. One of the most important gaps is the absence of objective methods for quantifying the monetary impact of risk events. The gaps found in the literature review and the feedback received from construction experts helped in identifying four important questions that are fairly addressed in this study. A structured approach was followed in this study to address the research questions. As a first stage, a questionnaire survey was

conducted among experts in the UAE construction industry to identify the most important risk events and provide their feedback in terms of the likelihood of occurrence, impact, and severity of these risk events. Construction experts identified 15 risk events to be the most important ones among 43 risks identified from the literature review. The findings of this study revealed that the “errors in the estimation of task durations” is considered the most probable risk event to happen, followed by the “scope change (additions/deletion)”, while the “weather conditions” risk event has the least probability of happening. In terms of the impact, the “poorly defined scope and inadequate design details” was ranked first followed by “complex design”, while the “weather conditions” risk event was ranked last. The severity of the “poorly defined scope and inadequate design details” risk event was ranked first, while the “scope change (additions/deletion)” risk event was ranked second. The “weather conditions” risk event was the least severe.

Interestingly, the feedback received from construction experts revealed that few construction practitioners are aware of the available risk management tools and techniques, and yet they avoid using these tools and techniques due to several reasons. One of the main reasons is that the majority of the available risk management tools and techniques are not applicable for construction projects. This is in addition to the complexity of these tools and techniques. One of the important questions addressed in this research is to provide project managers and other construction practitioners with a practical tool that helps them manage risk events related to construction activities. To this end, this study developed a spreadsheet framework as a second stage of the structured approach. The framework uses both qualitative and quantitative techniques through its risk severity matrix generation module, project scheduling module, quantitative risk analysis module, and risk response module. The quantitative risk analysis module uses the PERT and EV techniques to estimate the monetary effect of schedule and cost risks, measure the progress of the project’s schedule and cost, and estimate the severity of risks associated with the project’s schedule and bid price. A hypothetical example was then presented to illustrate the utilization, effectiveness, and validity of the proposed framework. The framework also suggests responses to risk events and presents a list of generic guidelines to mitigate risks in construction projects. The proposed framework, as such, is expected to help construction practitioners effectively assess the monetary impact and severity of risks associated with their projects in a practical and dynamic environments, while allowing them to update the data by adding new risk events, changing the levels of occurrence and impact, and adding responses to risk events.

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