Comprehensive Hybrid Framework for Risk Analysis in the Construction Industry Using Combined Failure Mode and Effect Analysis, Fault Trees, Event Trees, and Fuzzy Logic

Mohamed Abdelgawad, Ph.D., P.Eng.[1]; and Aminah Robinson Fayek, M.ASCE[2]

Abstract: The nature of the construction industry is characterized by many risks and uncertainty inherent in every phase of the project life cycle. Risk management, therefore, is essential for a construction project to succeed in fulfilling its project objectives. In conventional event-tree analysis, the probability of the risk event, the probability of failure/success of different mitigation strategies, and the consequences of different paths must be assessed to allow for quantitative event-tree analysis. However, conducting quantitative event-tree analysis, especially in construction projects, entails several difficulties attributed to the lack of sufficient data. To overcome this challenge, this paper presents a comprehensive framework in which experts can use linguistic terms rather than numerical values to conduct event-tree analysis and calculate the expected monetary value (EMV) of risk events. The proposed framework is based on combining failure mode and effect analysis (FMEA), fault trees, event trees, and fuzzy logic. This paper allows experts to express themselves linguistically to calculate the EMV of risk events, which is more appropriate for the construction domain. In addition, this paper introduces a comprehensive framework for risk management that combines three well-known techniques in reliability engineering in a novel way that considers the often subjective quality of risk-related data. The application of fuzzy logic provides an effective tool to handle subjectivity in the construction domain. The proposed framework is implemented in the form of two software tools entitled Risk Criticality Analyzer and Fuzzy Reliability Analyzer. To validate the framework, a case study is presented and the EMV is calculated using the proposed approach. The result of the proposed approach is then compared to the result obtained using Monte Carlo simulation, demonstrating that the proposed framework gives similar results to Monte Carlo simulation but provides the advantage of allowing experts to express themselves linguistically, making the proposed framework more practical and easier to apply in the construction domain. **DOI: 10.1061/(ASCE)CO.1943-7862.0000471.**

CE Database subject headings: Risk management; Fuzzy sets; Failure modes; Construction industry; Life cycles.

Author keywords: Risk management; Fuzzy sets; Failure modes.

Introduction

Over the past decade, many projects have experienced large variances in costs and schedules, which in turn impact profitability and cash flow. Different risk analysis techniques have been proposed in the past and used by researchers. For example, Haifang et al. (2009) used a risk matrix to identify the key risk events for private companies participating in a government project in China and to provide a basis for risk prevention. Although the risk matrix is simple to understand and use and can be calibrated to fit any type of project, this method is primarily a qualitative risk analysis technique, which has limited its use in assessing the expected monetary value (EMV) on capital projects (Abdelgawad and Fayek 2008). Mustafa and Al-Bahar (1991) used the analytical hierarchy process (AHP) to perform risk assessment of bridge construction. Significant risk events were identified and incorporated in the AHP model. The AHP is characterized as a multicriteria decision-making problem. One of the advantages of using AHP is its ability to measure the consistency of the analysis. However, a shortcoming of using the AHP method is the level of uncertainty and subjectivity of selecting a single number from the pairwise comparison scale. In addition, the output obtained from using the AHP is a scale number, which can only support qualitative risk analysis. Dey (2002) established a risk analysis model for a pipeline project in India based on combining the AHP with decision trees. Although the incorporation of decision trees is helpful in conducting quantitative risk analysis, this technique has some limitations. Thompson and Perry (1992) noted that adequate historical data are difficult to obtain to calculate accurate probability values for decision points to support decision tree analysis. Molenaar (2005) presented a methodology for cost and schedule risk analysis of highway megaprojects using Monte Carlo simulation. As with other techniques, using Monte Carlo simulation entails some difficulties, which are attributed to the amount of data required to establish probability distributions. Öztaş and Ökmen (2005) indicated that the assessment of the correlation coefficient between risk factors is important for any risk model, yet establishing these coefficients is difficult, especially if few or no data are available.

Fuzzy logic, which was first suggested by Zadeh (1965), has attracted several researchers in creating applications for the construction industry, especially in the field of risk analysis. Knight and Fayek (2002) indicated that most construction-related factors are subjective and uncertain, and thus fuzzy logic is very

[1]Risk Manager, Enbridge Pipelines Athabasca Inc., 10130 103 St. NW, Edmonton, AB, Canada T5J 3N9. E-mail: Mohamed.abdelgawad@enbridge.com

[2]Professor, NSERC Associate Industrial Research Chair, Ledcor Professor in Construction Engineering, Dept. of Civil and Environmental Engineering, Univ. of Alberta, Edmonton, AB, Canada T6G 2W2 (corresponding author). E-mail: aminah.robinson@ualberta.ca

Note. This manuscript was submitted on March 29, 2010; approved on August 15, 2011; published online on August 17, 2011. Discussion period open until October 1, 2012; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 138, No. 5, May 1, 2012. ©ASCE, ISSN 0733-9364/2012/5-642–651/$25.00.

satisfactory at modeling construction issues where usually the information is largely available in the mind of an experienced construction practitioner. Dikmen et al. (2007) introduced a fuzzy risk analysis tool to quantify risk ratings in the construction domain at an early phase of a project. Nasirzadeh et al. (2008) presented a model for risk analysis that considers the interrelationships and interactions between risk events. Gürcanli and Müngen (2009) proposed a fuzzy expert system to assess the risks that workers are exposed to on construction sites. Although fuzzy logic offers the advantage of using linguistic terms to assess the level of risk in the construction industry, most of the previous models are either qualitative models or are limited in their application, since calibration was not considered. In addition, most of these studies focused on assessing the risk level, i.e., probability times impact, without considering the level of risk criticality as it relates to the type of response and the priority the risk required.

This paper offers the contribution of introducing a framework for conducting risk analysis based on combining fuzzy logic with three well-known techniques in reliability engineering [failure mode and effect analysis (FMEA), fault trees, and event trees] in a novel way, while considering the subjective characteristics of risk-related data. Using the proposed framework, the criticality of risk events is first calculated using fuzzy FMEA (Abdelgawad and Fayek 2010). Critical risk events identified using fuzzy FMEA are further analyzed using fuzzy fault-tree analysis (Abdelgawad and Fayek 2011). The fault tree structure is established to connect each critical risk event (top event) to its basic events. The probabilities of basic events are defined using possibility distributions, and experts use linguistic terms to assess the probability of occurrence of basic events, referred to as fuzzy probabilities. Fuzzy arithmetic operations are applied thereafter to conduct quantitative fuzzy fault-tree analysis of the critical risk events (Abdelgawad and Fayek 2011). Thereafter, mitigation strategies are identified and analyzed by assessing the fuzzy probability of failure of potential mitigation strategies. The calculated fuzzy probability of critical risk events and the fuzzy probability of failure of potential mitigation strategies are used as inputs to conduct fuzzy event-tree analysis to estimate the EMV of critical risk events, as will be explained in this paper. The proposed integration between FMEA, fault trees, event trees, and fuzzy logic is also introduced and highlighted in this paper.

The study by Abdelgawad and Fayek (2010), introduced the concept of risk criticality analysis and used it to overcome some of the limitations of previous techniques by supporting the screening of critical risk events. The study by Abdelgawad and Fayek (2011), introduced the concept of fuzzy fault tree analysis and provided users with the ability to conduct fault-tree analysis, even if data were lacking, and offered a transparent framework to calculate the fuzzy probability of occurrence of risk events. In the present paper, the writers introduce the concept of fuzzy event-tree analysis and provide a comprehensive framework based on combining FMEA, fault trees, event trees, and fuzzy logic in a novel way to support risk criticality assessment and risk analysis. This framework provides risk analysts with the ability to conduct event-tree analysis even if data are not available, and provides a transparent framework to track the calculated EMV of risk events and verify the results. In addition, this framework provides the project management team with the ability to analyze risk response strategies and to calculate the fuzzy probability of failure of each mitigation strategy. Thus, more cost-efficient risk response strategies can be developed by examining options that reduce the chances of failure. Moreover, this paper provides a flexible framework in which membership functions can be calibrated to suit different contexts. The next sections provide an introduction to FMEA, fault trees, and event trees.

Reliability Engineering Techniques

Failure Mode and Effect Analysis

FMEA was first established by the U.S. military in 1949 (McDonald et al. 2008). In the early 1960s, the U.S. military established a military standard (MIL-STD-1629A; U.S. Dept. of Defense 1980) for conducting FMEA (McDonald et al. 2008). Within any traditional FMEA framework, risk analysis starts from the component level of the system, works on compiling a list of potential failure modes, and tries to infer the effects of those failure modes on the system by calculating an index score called the risk criticality number. The risk criticality number ranges from 1 to 1,000 and is calculated by multiplying three variables: the probability of occurrence, the severity, and the level of detection/control. According to the value calculated for the risk criticality number, risk mitigations are established. The reader can refer to Abdelgawad and Fayek (2010) for a detailed explanation of risk criticality analysis using fuzzy FMEA.

Fault-Tree Analysis

The concept of fault-tree analysis (FTA) was first introduced in 1961 by H. A. Watson of Bell Laboratories by an order of the U.S. Air Force (Ericson 1999). In 1963, Boeing was the first commercial company to develop an FTA program. Since then, FTA has been utilized to assess failures in the nuclear industry, and significant advancements have been made by developing algorithms and software to solve fault trees (Ericson 1999). The analysis of a fault tree starts by determining the immediate causes for the occurrence of the top event, which are referred to as intermediate events or gate events. The intermediate events (gate events) are then treated as subtop events, and the analyst proceeds to determine their immediate causes. The analysis continues until reaching basic events, which represent the lowest level in a fault-tree structure; basic events and gate events are referred to as "root causes." Logical gates combine the root causes with the top event. AND (intersection) and OR (union) gates are commonly used to connect root causes. The AND gate indicates that all of the lower events must occur for the upper event to occur. The OR gate indicates that the occurrence of any one of the events in the lower level is sufficient for the upper event to occur.

Fault trees can be solved qualitatively and quantitatively. Qualitative fault-tree analysis is performed by identifying the minimal cut sets. Ayyub (2003) defined a minimal cut set as "a cut set with the condition that the non-occurrence of any one basic event from this set results in the non-occurrence of the top event." In other words, qualitative fault-tree analysis is conducted to convert a fault-tree structure into an equation showing the logic that can lead to the occurrence of the top event. Quantitative fault-tree analysis is performed by calculating the top event probability of occurrence by substitution into the equation established using qualitative fault-tree analysis. Abdelgawad and Fayek (2011) proposed a comprehensive framework for fuzzy fault-tree analysis and automated fuzzy fault-tree analysis in a piece of software named Fuzzy Reliability Analyzer.

Event-Tree Analysis

Event trees are inductive techniques intended to examine a sequence of events and their probability of occurrence. The event tree starts with an initiating event or risk event, and proceeds

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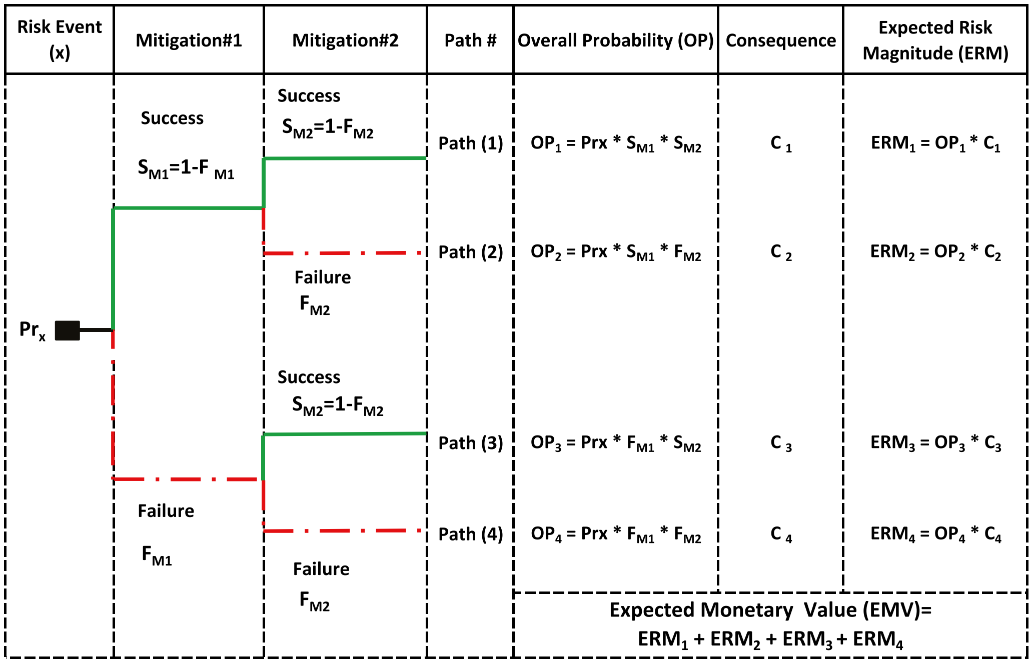

Fig. 1. Example of event-tree analysis [reprinted with permission from (Abdelgawad 2011)]

sequentially by adding risk response strategies, represented by branches, to mitigate the initiating event (Ahmadi and Soderhölm 2008).

To explain the traditional approach of conducting event-tree analysis (ETA), consider the event-tree structure shown in Fig. 1, which is composed of a risk event (X) mitigated using two mitigation strategies, referred to as mitigation 1 ($M1$) and mitigation 2 ($M2$). The probability of occurrence of the risk event is defined as (P), the probability of failure of mitigation 1 is defined as (F_{M1}), and the probability of failure of mitigation 2 is defined as (F_{M2}). In this example, assume that there are enough data to estimate the probability of occurrence of the risk event and the probability of failure of each mitigation strategy, such that $P = 0.50$, $F_{M1} = 0.40$, and $F_{M2} = 0.30$. According to Fig. 1, the probability of success of mitigation 1 (S_{M1}) and the probability of success of mitigation 2 (S_{M2}) are calculated as follows:

$$S_{M1} = 1 - F_{M1} = 1 - 0.40 = 0.60 \tag{1}$$

$$S_{M2} = 1 - F_{M2} = 1 - 0.30 = 0.70 \tag{2}$$

The overall probability (OP) of each path is then calculated by multiplying the probability of events located on the selected path. For instance, path (1) indicates that the risk event has occurred, and mitigation 1 and mitigation 2 were both successful in mitigating the risk event. Accordingly, the OP of path (1) is calculated as follows:

$$OP_1 = P \times S_{M1} \times S_{M2} = 0.50 \times 0.6 \times 0.70 = 0.21 \tag{3}$$

The same concept can be applied to calculate OP_2 to OP_4.

To calculate the expected risk magnitude of path (1) (ERM_1), assume that the estimated consequence (C_1) of path (1) is \$300,000. Thus, the ERM_1 is calculated as follows:

$$\mathrm{ERM}_1 = OP_1 \times C_1 = 0.21 \times \$300{,}000 = \$63{,}000 \tag{4}$$

The same concept can be applied to calculate ERM_2 to ERM_4. In this example, assume that ERM_2, ERM_3, and ERM_4 are estimated as follows:

$$\mathrm{ERM}_2 = \$78{,}000 \tag{5}$$

$$\mathrm{ERM}_3 = \$80{,}000 \tag{6}$$

$$\mathrm{ERM}_4 = \$85{,}000 \tag{7}$$

Accordingly, the EMV can be estimated as follows:

$$\mathrm{EMV} = \mathrm{ERM}_1 + \mathrm{ERM}_2 + \mathrm{ERM}_3 + \mathrm{ERM}_4 = \$306{,}000 \tag{8}$$

Since 1960, several research studies have been conducted using event trees for different applications. For instance, Novack et al. (1997) investigated the use of event trees to analyze accident scenarios attributed to oil spills, and Hong et al. (2009) analyzed the risk of an underwater tunnel excavation using an earth pressure balance type tunnel boring machine. The traditional application of ETA requires enough data to estimate the probability of occurrence of events and to assess their consequences, which are often difficult to obtain in the construction domain.

The next section illustrates the proposed integration between FMEA, event trees, fault trees, and fuzzy logic to provide a quantitative assessment of critical risk events.

Proposed Hybrid Framework

Although the concept of FMEA has been applied in many different disciplines, several authors have noted concerns related to the traditional FMEA approach for calculating the risk criticality number (e.g., Bowles and Peláez 1995; Puente et al. 2002). Abdelgawad and Fayek (2010) proposed a comprehensive framework to address the limitations of the traditional calculation of the risk criticality number by incorporating fuzzy logic with traditional FMEA and AHP techniques. Within the proposed framework, fuzzy logic is combined with FMEA and used to establish a fuzzy expert system. Inputs to the fuzzy expert system consist of the probability of occurrence, aggregated impact, and detection/control of each risk

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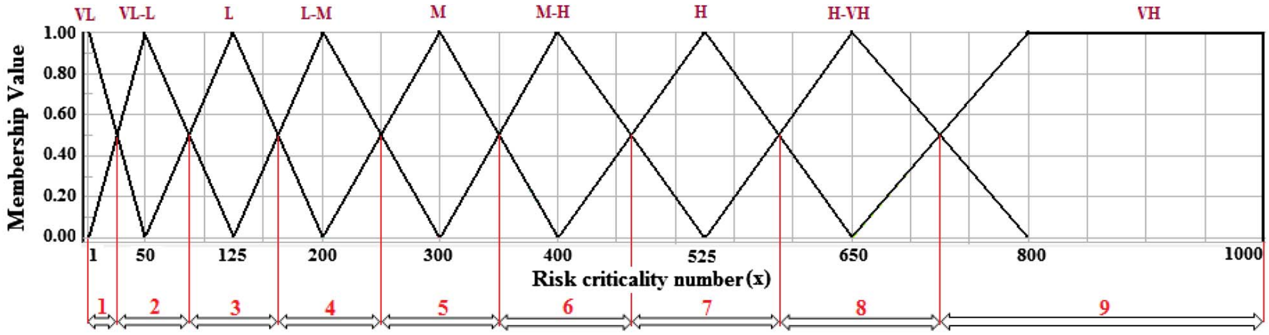

Label	Corrective Action Categories	Risk criticality Number (X)
1	No corrective action is required	x < 25.5
2	Unnecessary to take any corrective action(s)/accept	25 ≤ x < 87.5
3	Low priority to take any corrective action(s)/accept	87.5 ≤ x < 162.5
4	Somewhat moderate priority to take corrective action(s) /consider mitigation	162.5 ≤ x < 250
5	Moderate priority to take corrective action(s)/ consider mitigation or transfer	250 ≤ x < 350
6	Somewhat high priority to take corrective action(s)/ consider mitigation or transfer	350 ≤ x < 462.5
7	High priority to take corrective action(s)/ consider avoidance or transfer	462.5 ≤ x < 587.5
8	Necessary to take corrective action(s)/ consider avoidance or transfer	587.5 ≤ x < 725
9	Absolutely necessary to take corrective action(s)/ consider avoidance options	x≥ 725

Fig. 2. Membership functions of the risk criticality number and corrective action categories [reprinted from Abdelgawad and Fayek (2010), ASCE]

event, i.e., three inputs that range from 1 to 10. This range is covered using five linguistic terms, i.e., very low, low, medium, high, and very high. The aggregated impact is defined over three variables—namely, cost impact, time impact, and scope/quality impact—all of which range from 1 to 10; this range is covered using the same five linguistic terms. Since there are three inputs to the fuzzy expert system, the aggregated impact must be calculated first. In this regard, the concept of fuzzy AHP is utilized to aggregate the cost impact, time impact, and scope/quality impact. The relative importance to the project objectives between time impact versus cost impact, cost versus scope/quality impact, and time impact versus scope/quality impact is captured from a senior risk coordinator using a standard trapezoidal fuzzy number, i.e., four parameters (a, b, c, d). For example, when comparing time impact versus scope/quality impact, the expert believed that at a minimum, the time impact is equally to moderately more important than the scope/quality impact (i.e., $a = 2$); the most likely is that time is moderately more important than scope/quality impact (i.e., $b = c = 3$); and the maximum is that time impact is moderately to strongly more important than scope/quality impact (i.e., $d = 4$). The numerical values of the linguistic assessment of the four parameters ($a = 2$, $b = 3$, $c = 3$, $d = 4$) were obtained using Saaty's pairwise comparison scale (Abdelgawad and Fayek 2010). The defuzzified value of the preference of time impact versus scope/quality impact (D_{TS}) was calculated as follows:

$$D_{TS} = \frac{a + 2 \times (b + c) + d}{6} = \frac{2 + 2 \times (3 + 3) + 4}{6} = 3 \tag{9}$$

The same concept is applied to calculate the defuzzified value of the preference of time impact versus cost impact (D_{TC}) and the defuzzified value of the preference of cost impact versus scope/quality impact (D_{CS}). The defuzzified value of the preferences, i.e., D_{TS}, D_{TC}, D_{CS}, and their reciprocal value are used to establish the AHP matrix. Standard AHP calculations and consistency analysis are conducted, which results in the following equation (Abdelgawad and Fayek 2010):

$$\text{Aggregated impact} = 0.40 \times \text{cost impact} + 0.46 \times \text{time impact} + 0.14 \times \text{scope/quality impact} \tag{10}$$

The calculated consistency index is less than 0.1, which indicates that the results of fuzzy AHP are consistent (Abdelgawad and Fayek 2010). To calculate the risk criticality number, the user is required to provide an assessment of cost impact, time impact, scope/quality impact, probability of occurrence, and detection/control. For example, assume that the following assessments were provided: probability of occurrence = 4, cost impact = 3, time impact = 5, scope/quality impact = 4, and detection/control = 4. First, the aggregated impact is calculated using Eq. (10) as follows:

$$\text{Aggregated impact} = 0.40 \times 3 + 0.46 \times 5 + 0.14 \times 4 = 4.06 \tag{11}$$

Second, the assigned value for probability of occurrence and detection/control together with the calculated aggregated impact are used as input to the fuzzy expert system to calculate the risk criticality number. A total of 125 rules were elicited from a senior risk coordinator and used to build the fuzzy expert system. The fuzzy expert system fires the appropriate rules, aggregates the inputs, performs rule implication and aggregation, and defuzzies the results using the center of area method to calculate the risk criticality number (Abdelgawad and Fayek 2010). The following is a sample if-then rule:

If aggregated impact is "low" and probability of occurrence is "low" and detection/control is "high" then risk criticality number is "very low."

The risk criticality number ranges from 1 to 1,000 and is defined using nine linguistic terms (very low, very low-low, low, low-medium, medium, medium-high, high, high-very high, and very high). Fig. 2 shows the values of the risk criticality number and the ranges for each recommended corrective action (Abdelgawad 2011). The fuzzy FMEA and fuzzy AHP approaches are implemented in decision support software called Risk Criticality Analyzer (Abdelgawad and Fayek 2010). Fig. 3 presents the

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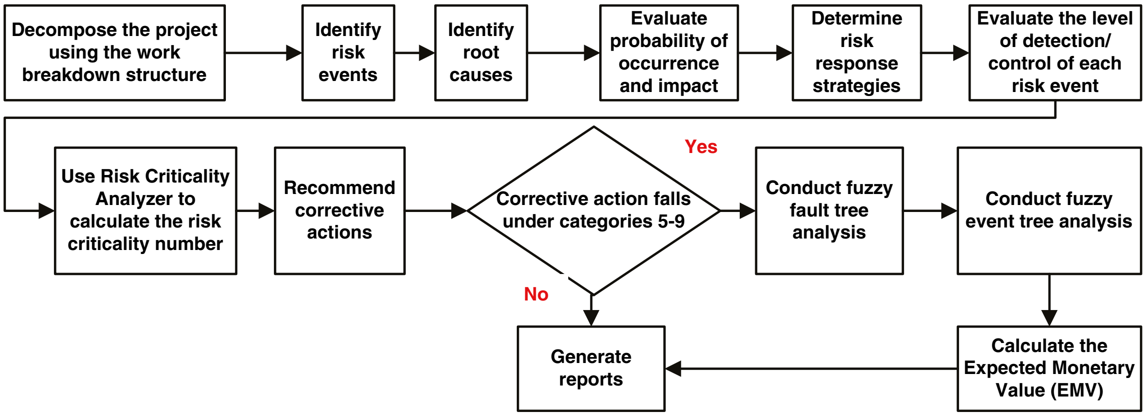

Fig. 3. Proposed framework to integrate FMEA, fault trees, event trees, and fuzzy logic

proposed framework to integrate FMEA, fault trees, event trees, and fuzzy logic, which is described next.

Fig. 3 illustrates how this concept is applied. First, each project is broken down into its main components using the work breakdown structure, and each work package is analyzed to identify different risk events. Root-cause analysis is conducted to identify the immediate root causes of each risk event, i.e., the first level of root cause (basic events and gate events). The probability of occurrence, cost impact, time impact, and scope/quality impact are evaluated for each identified risk event using linguistic terms. Each risk event is then assigned a preliminary mitigation strategy to minimize its immediate root causes. Accordingly, an evaluation of the level of detection/control for each mitigation strategy is made, and the risk criticality number is calculated using the Risk Criticality Analyzer. Any risk event that is assessed using the Risk Criticality Analyzer to obtain a risk criticality number that falls in the range defined by categories 5 to 9 shown in Fig. 2 is required to undergo detailed risk analysis using fuzzy fault-tree and fuzzy event-tree analyses, as explained in the next section.

Risk Analysis Using Combined Fuzzy Fault-Tree and Fuzzy Event-Tree Analyses

Using FMEA, root causes are identified and listed without any further analysis. Risk mitigation strategies as obtained during FMEA are high-level mitigation strategies. By using fault-tree analysis, all the identified root causes using FMEA are further analyzed and interconnected using AND/OR operators to establish a fault-tree structure. In addition, preliminary mitigation strategies are further analyzed. To explain how the findings of the FMEA are further explored during fault-tree analysis, assume that a risk event was identified using failure model and effect analysis called "failure of establishing of proper field process." Assume that the following root causes were identified using FMEA: inadequate follow-up training, loss of key resources, and lack of documentation of communication requirements. These root causes are further analyzed, and the logic is established between root causes to establish a fault-tree structure, as shown in Fig. 4.

Since all mitigation strategies identified during FMEA are preliminary strategies, further analysis is required during fault-tree analysis. For example, using FMEA, the preliminary risk mitigation strategies for the identified risk event, "failure of establishing of proper field process," would be to establish training, look for options to mitigate the loss of key personnel, and establish communication requirements. By establishing a fault-tree structure, more detailed mitigation strategies can be established. For example, to establish proper training, an adequate budget needs to be allocated and each project must budget enough time to train people, as shown in Fig. 4. The same concept can be applied to establish detailed mitigation strategies to mitigate the loss of key personnel and to establish communication requirements.

Fuzzy fault-tree and fuzzy event-tree analyses are combined to support risk analysis in the construction domain. Fuzzy fault-tree analysis is utilized to calculate the fuzzy probability of occurrence of the risk events and the failure probability of each identified mitigation strategy. Since the risk event and the failure of mitigation strategies are represented using different fault-tree structures,

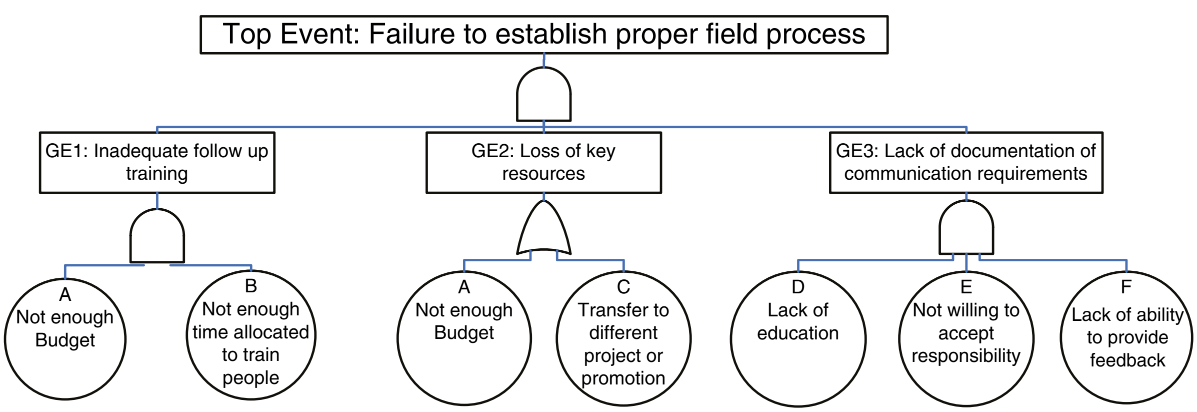

Fig. 4. Example of fault-tree structure [reprinted with permission from (Abdelgawad 2011)]

Table 1. Trapezoidal Representation of Probability of Occurrence (0 to 100)

Linguistic terms	Probability of occurrence, % *a*	*b*	*c*	*d*
Very high	50	67	100	100
High	21	33	50	67
Medium	5	10	21	33
Low	0	1	5	10
Very low	0	0	0	1

several fuzzy fault-tree analyses are conducted. For instance, if a risk event is mitigated using two mitigation strategies, then three fuzzy fault-tree analyses are conducted to calculate the fuzzy probability of the risk event and the fuzzy probability of failure of each identified mitigation strategy. An event-tree structure is then established according to the identified mitigation strategies. The outcomes of conducting fuzzy fault-tree analysis are used to define the fuzzy probability of the risk event together with the failure branches of the event tree. The consequence (C) of each path in the event tree is then assessed using linguistic terms. Fuzzy event-tree analysis is then conducted to estimate the expected monetary value of each risk event. The following steps describe the approach taken to integrate fuzzy fault-tree and fuzzy event-tree analyses.

Step 1: Establish Membership Functions to Assess Probability of Occurrence and Impact

To establish membership functions to assess the fuzzy probability of basic events and the impact (consequence) of risk events, an interview was conducted with the same senior risk coordinator. The interview started by reviewing the approach used by the company to assess the probability of occurrence and the impact (consequence) of risk events, as defined in the company risk management standard. The company uses five linguistic terms [very low (VL), low (L), medium (M), high (H), and very high (VH)] to assess the probability of occurrence and impact of risk events. The probability of occurrence is defined as the likelihood of occurrence of the risk event. The impact is defined as the percentage of the baseline cost estimate. The same expert was consulted to establish the membership function for each linguistic term for both probability of occurrence and impact, using the direct method (Klir and Yuan 1995). The range of each linguistic term is defined using a standard trapezoidal fuzzy number (a, b, c, d), where a represents the minimum value, b and c represent the endpoints of the range of the most likely values, and d represents the maximum value of the membership function (MF). Table 1 shows the trapezoidal representation of the membership functions that represent the probability of occurrence. Table 2 shows the trapezoidal representation of the membership functions that represent the impact (consequence). The range of each linguistic term can be calibrated to suit a different organization or context by re-eliciting the values for each standard trapezoidal fuzzy number. The introduction of linguistic terms to assess the probability of occurrence and the impact (consequence) of the risks can help in conducting fault-tree and event-tree analyses in the construction domain, even if data are unavailable or difficult to obtain.

Table 2. Trapezoidal Representation of Impact (Consequence) (0 to 100)

Linguistic terms	Impact (consequence), % *a*	*b*	*c*	*d*
Very high	6	10	100	100
High	1.1	2	6	10
Medium	0.11	0.2	1.1	2
Low	0.01	0.02	0.11	0.20
Very low	0	0	0.01	0.02

Step 2: Conduct Fuzzy Fault-Tree Analysis for Risk Events and Mitigation Strategies

To conduct fuzzy fault-tree analysis for the risk events and their associated mitigation strategies, the following steps are followed:

1. Input from experts is used to construct fault trees and to assess the fuzzy probability of basic events. In this regard, interviews were conducted with the same risk expert, and logical gates (AND/OR) were used to define the logic between the risk event and its root causes (basic events and gate events). The linguistic terms in Table 1 were used to assess the fuzzy probability for basic events.
2. Different mitigation strategies that can be used to minimize or eliminate the initiating event/risk event and different root causes (basic events and gate events) that can lead to the failure of each mitigation strategy are identified. Fault-tree structures are developed to define the failure of each mitigation strategy and to assess the fuzzy probability of basic events using the linguistic terms in Table 1.
3. Several fuzzy fault-tree analyses are conducted using the Fuzzy Reliability Analyzer to calculate the fuzzy probability of the risk event and to calculate the fuzzy probability of the failure of each mitigation strategy (Abdelgawad and Fayek 2011). For example, assume that a risk event was identified and three mitigation strategies were established. In this case, four fuzzy fault-tree analyses are conducted: one to calculate the fuzzy probability of the risk event and three to calculate the fuzzy probability of failure of each mitigation strategy. In this regard, qualitative fault-tree analysis is applied first to transform the logical relationship between the top event and basic events into mathematical equations, known as minimal cut sets, by applying Boolean algebra. Abdelgawad and Fayek (2011) applied Hauptmanns' algorithm (1988) to conduct qualitative fault-tree analysis. The reader can refer to Abdelgawad and Fayek (2011) for more details.

Step 3: Conduct Fuzzy Event-Tree Analysis

After conducting fuzzy fault-tree analysis and calculating the fuzzy probability of the risk event and the fuzzy probability of failure of the mitigation strategies, fuzzy event-tree analysis is conducted as follows:

1. The event-tree structure is constructed according to the number of mitigation strategies identified in step 2. The consequence (C; impact) of each path is assessed using the linguistic terms in Table 2. For explanation purposes, assume that two mitigation strategies are identified, and thus the event-tree structure is the same as in Fig. 1.
2. The outcomes of fuzzy fault-tree analyses are used to define the fuzzy probability of the risk event and the fuzzy probability of failure. The fuzzy probability of success of different mitigation strategies is calculated as follows:

$$\begin{aligned}&\text{Fuzzy probability of success}\\&= 1 - \text{fuzzy probability of failure}\end{aligned} \tag{12}$$

Eq. (12) is equivalent to Eqs. (1) and (2) represented in the fuzzy domain.

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3. The OP of each path is calculated by multiplying the fuzzy probability of all events located on the same path. This step is similar to Eq. (3). To explain further, assume that the fuzzy probability of the risk event, the fuzzy probability of success of mitigation 1, and the fuzzy probability of success of mitigation 2 are calculated as 0.80, 0.60, and 0.42, respectively, using the Fuzzy Reliability Analyzer. Thus, the OP of path (1) is calculated as follows:

$$\mathrm{OP}_1 = 0.80 \times 0.60 \times 0.42 = 0.20 \tag{13}$$

4. The OP of each path, calculated in the previous step, is multiplied by the estimated consequence (C) of each path to calculate the expected risk magnitude (ERM) of each path. This step is similar to Eqs. (4)–(7), except that the impact (consequence) is represented using a trapezoidal distribution. To illustrate this step, assume that the consequence of path (1) is estimated as low (L): 0.01, 0.02, 0.11, and 0.20 (Table 2). Thus, the ERM for path (1) is calculated as follows:

$$\begin{aligned}\mathrm{ERM}_1 &= \mathrm{OP}_1 \times C_1 = 0.20 \times (0.01, 0.02, 0.11, 0.20) \\ &= (0.002, 0.004, 0.022, 0.040)\end{aligned} \tag{14}$$

   The same concept can be used to estimate ERM_2 to ERM_4.

   In this step, the consequence of the risk event is assessed by experts using linguistic terms rather than using numerical values, making the event-tree analysis easier to conduct and more suitable to the construction domain.

5. Fuzzy arithmetic operations are used on the resulting fuzzy numbers representing the ERM of each path to calculate the EMV as follows:

   If A and B are two trapezoidal fuzzy sets representing the ERM, where $A^\alpha = [a_1 b_1 c_1 d_1]$ and $B^\alpha = [a_2 b_2 c_2 d_2]$, then the sum of A and B is defined as shown in Eq. (15) (Verma et al. 2007). The α-cut of a fuzzy set A is the set of all x values in the set for which the membership degree in the fuzzy set is greater than or equal to the alpha (α) argument.

$$A^\alpha + B^\alpha = [a_{1+}a_2, b_{1+}b_2, c_{1+}c_2, d_{1+}d_2] \tag{15}$$

   For explanation purposes, assume that the ERM for path (2) to path (4) in Fig. 1 is calculated as follows: $\mathrm{ERM}_2 = (0.004, 0.006, 0.031, 0.080)$, $\mathrm{ERM}_3 = (0.005, 0.009, 0.045, 0.085)$, and $\mathrm{ERM}_4 = (0.007, 0.12, 0.150, 0.190)$.

   Thus, using Eq. (15), the EMV is calculated as follows:

$$\begin{aligned}\mathrm{EMV} &= \mathrm{ERM}_1 + \mathrm{ERM}_2 + \mathrm{ERM}_3 + \mathrm{ERM}_4 \\ &= (0.018, 0.139, 0.248, 0.395)\end{aligned} \tag{16}$$

6. The mean of maximum (MOM) method of defuzzification is applied to the fuzzy number representing EMV, as calculated in Eq. (16), to provide a crisp estimate of the EMV of the risk event. Since the membership function at $\alpha = 1$ represents the most confident level, the mean of maximum can be viewed as the most likely estimate of probability over the most confident range. In this example, the MOM is calculated as follows:

$$\mathrm{EMV} = \frac{b + c}{2} = \frac{0.139 + 0.248}{2} = 0.194\,\% \tag{17}$$

   If, for example, the estimated baseline cost of this project is \$100,000,000, then the EMV in Eq. (17) can be represented as a dollar value as follows:

$$\mathrm{EMV} = 0.194\% \times 100{,}000{,}000 = \$194{,}000 \tag{18}$$

Eq. (18) shows the EMV for risk after conducting fuzzy fault-tree analysis and fuzzy event-tree analysis. This dollar value represents the risk premium associated with the risk event. The fuzzy fault-tree analysis is helpful in understanding the logic behind the occurrence of the risk event. The fuzzy event-tree analysis is helpful in determining the EMV using linguistic terms to assess the impact (consequence) of each path of the event tree. To automate the quantitative fuzzy event-tree analysis (step 3), an extra module was added to the Fuzzy Reliability Analyzer using Microsoft Visual Studio 2008 to support fuzzy event-tree analysis.

Case Study

To verify the validity of the proposed framework in the construction domain, a pipeline project was selected. The scope of the selected project includes the installation of a new crude oil pipeline with an initial capacity of 350,000 bpd. The total length of the pipeline is 380 km. Horizontal directional drilling failure to meet the project objectives was identified as a critical risk event using the Risk Criticality Analyzer (i.e., risk criticality number falls between categories 5 to 9), and hence a detailed risk analysis was required using fuzzy fault-tree and fuzzy event-tree analyses.

To establish the fault-tree structure for the risk event, several interviews were conducted with the same senior risk coordinator and another risk engineer working in the pipeline company that provided the case study. Basic events and intermediate events were identified and connected using AND/OR gates. The fuzzy probabilities of occurrence of basic events were assessed using the linguistic terms in Table 1. The Fuzzy Reliability Analyzer was then used to conduct qualitative and quantitative FTA of the fault tree. The fuzzy probability of the risk event was calculated using the Fuzzy Reliability Analyzer as 0.79. The reader can refer to Abdelgawad and Fayek (2011) for a detailed qualitative and quantitative FTA of the risk event. Given the high probability of this risk event, several interviews were conducted again with both experts to identify suitable mitigation strategies. Three mitigation strategies were identified as follows:

- Mitigation 1: establish a proper prequalification strategy to select the right contractor.
- Mitigation 2: establish a proper procedure to select the right drilling location.
- Mitigation 3: establish a contingency plan to control the risk, if realized.

The two experts were asked to identify the root causes (basic events and gate events) of failure of each mitigation strategy and to assess the fuzzy probability of occurrence of each basic event. For instance, the failure of mitigation 1 is defined as failure to select the right contractor. Two basic events were identified: nonavailability of a horizontal directional drilling (HDD) contractor with the required experience at the time and location required (basic event A), and failure to establish objective selection criteria and enforce them during the bidding stage (basic event B). The logic indicates that the occurrence of either A or B or both can lead to the failure of mitigation 1. Thus, the OR gate was used to connect the basic events A and B to the top event. Both basic events were assessed to have medium (M) probability of occurrence, using the linguistic terms defined in Table 1. A similar process was followed to evaluate the basic events of failure of the other two mitigation strategies. Fig. 5 shows a summary of the findings for the failure of mitigation 1, mitigation 2, and mitigation 3. The Fuzzy Reliability Analyzer was then used to conduct qualitative and quantitative fault-tree analysis for the fault trees presented in Fig. 5. Using the Fuzzy Reliability Analyzer, the fuzzy probability of failure

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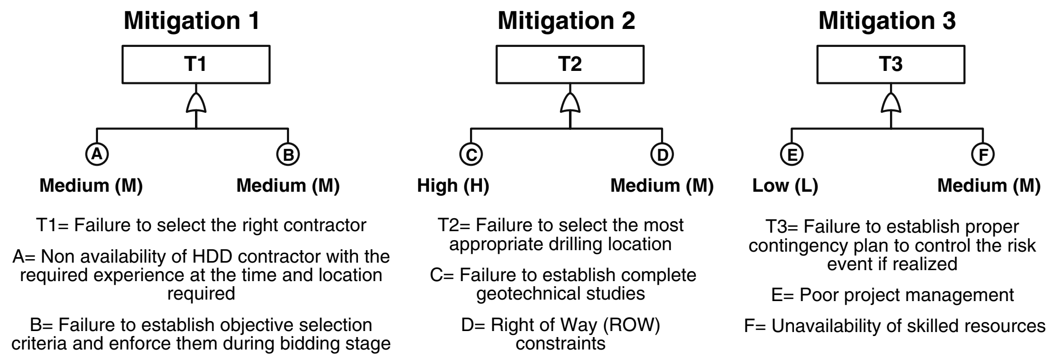

Fig. 5. Fault-tree analysis of mitigation strategies [reprinted with permission from (Abdelgawad 2011)]

of each mitigation strategy was calculated as follows: fuzzy probability of failure of mitigation 1 = 0.29, fuzzy probability of failure of mitigation 2 = 0.50, and fuzzy probability of failure of mitigation 3 = 0.18. Given the limited availability of data in the construction industry, fuzzy logic was successfully utilized to estimate the fuzzy probability of occurrence of the risk event and the failure of the mitigation strategies by using linguistic terms to assess the fuzzy probability of basic events and fuzzy arithmetic operations to conduct quantitative fault-tree analysis (Abdelgawad and Fayek 2011).

The event-tree structure was then established by considering the three mitigation strategies, and the results from the fuzzy fault-tree analysis were used to define the fuzzy probability of the risk event and the fuzzy probability of failure of each mitigation strategy. The fuzzy probability of success of each mitigation strategy was then calculated according to Eq. (12). Both experts were further asked to assess the consequence (C) for each path by considering the events located on the path. Fig. 6 shows the assessment of the consequence of each path as determined by the experts. Fig. 6 also shows the EMV of the risk event after conducting fuzzy event-tree analysis. The EMV is estimated to be 0.27% of the baseline cost estimate. This percentage can be converted to a dollar value by multiplying it by the estimated baseline cost. Using fuzzy arithmetic operations, the event tree was successfully analyzed even in this scenario where data were not available to assess the consequence of each path.

To validate the findings of the proposed framework, a Monte Carlo simulation model was developed for the case study, and its results were compared to the results obtained using the proposed framework. To develop the simulation model, an interview was arranged with a construction manager with more than 30 years of experience. A detailed report of the case study, the fault-tree structure, and the fuzzy probability of basic events was presented to the construction manager. The construction manager was asked to provide an assessment of the probability of the risk event and the cost impact, which is represented using three points, i.e., minimum,

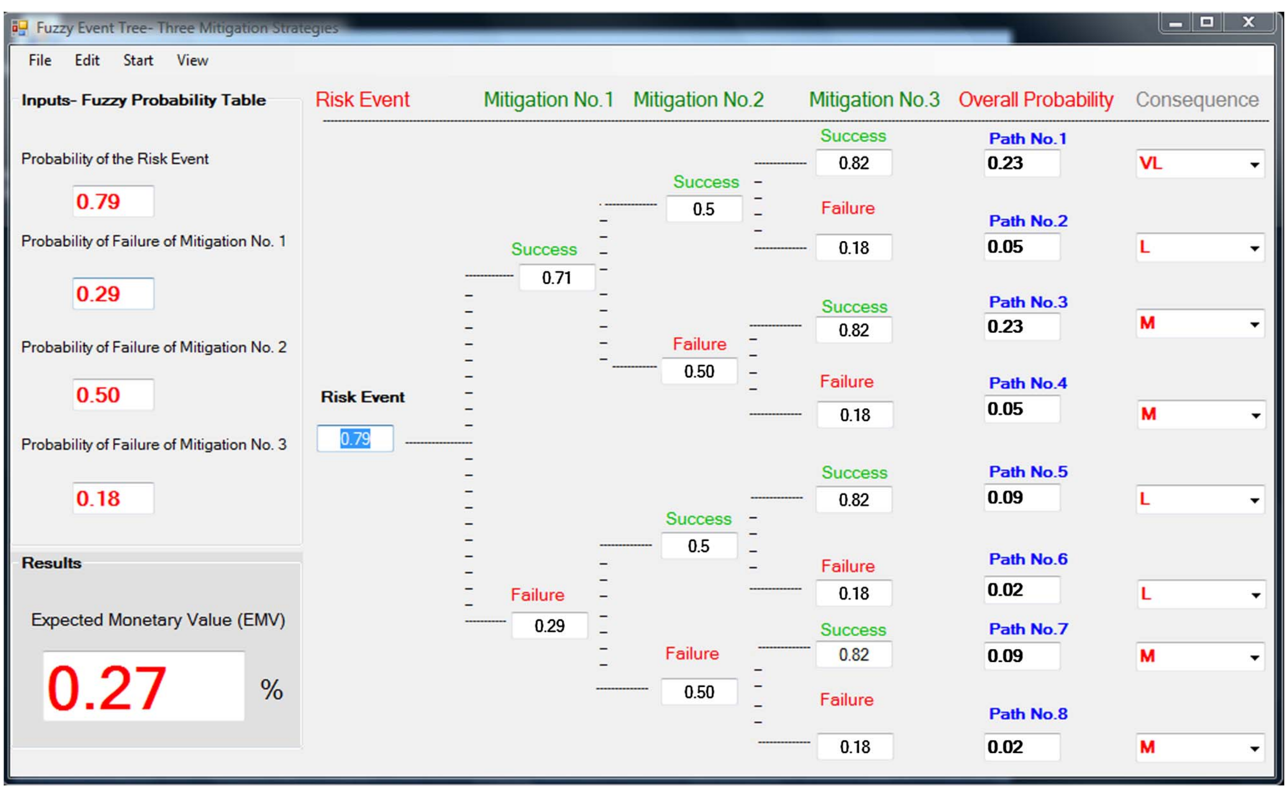

Fig. 6. Fuzzy Reliability Analyzer: fuzzy event-tree calculations [reprinted with permission from (Abdelgawad 2011)]

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most likely, and maximum. The assessment of the probability of occurrence (P) and the cost impact are as follows: $P = 0.50$, minimum cost impact = 0.06%, most likely cost impact = 0.14%, maximum cost impact = 0.52%. The cost impact is represented as a percentage of the baseline cost estimate. This percentage can be converted to a dollar value by multiplying it by the estimated baseline cost. After collecting the required information, the EMV of the risk event was represented using a triangular distribution, and 1,000 iterations were conducted to calculate the EMV. The results of the Monte Carlo simulation indicate that the calculated mean cost value of this risk is equal to 0.24% of the project baseline cost, as compared to 0.27% using the Fuzzy Reliability Analyzer (FRA), indicating comparable results.

A comparison of the proposed approach with the Monte Carlo simulation leads to the following conclusions:

- The use of fuzzy logic offers a transparent approach, as demonstrated in step 3 previously described, to track the EMV as compared to using a Monte Carlo simulation approach, in which random numbers are generated and used to calculate the results.
- The use of fuzzy logic allows experts to use linguistic terms to assess the probability of occurrence and impacts, which better suits the way experts make such evaluations. Such an advantage is not provided by Monte Carlo simulation in which experts are required to provide numerical values of the probability of occurrence and impacts.
- The use of fault trees provides experts with the ability to understand the root causes of the risk event. Such an advantage is not offered by Monte Carlo simulation.
- The use of event-tree analysis provides experts with the ability to visualize and explore a series of risk mitigation scenarios to calculate the EMV. Monte Carlo simulation does not offer such flexibility.

The proposed hybrid framework using FMEA, fault trees, event trees, and fuzzy logic was illustrated using one critical risk event to demonstrate the concepts. The same technique can be applied to assess any number of critical risk events in a construction project, or even at the portfolio level of a company, by using an appropriate risk register template to collect information from the relevant experts, and by applying each of the steps outlined in this paper.

Conclusions and Future Research

This paper introduces the concept of fuzzy event-tree analysis and provides a comprehensive framework based on a combination of fuzzy logic with FMEA (Abdelgawad and Fayek 2010), fault trees (Abdelgawad and Fayek 2011), and event trees to provide a practical and thorough approach for assessing the level of criticality of risk events in the construction domain and in supporting quantitative risk analysis. Fuzzy logic was utilized to address the limitations of the traditional application of FMEA, fault trees, and event trees. Using this framework, risk experts can identify critical risk events (Abdelgawad and Fayek 2010), assess the probability of basic events linguistically (Abdelgawad and Fayek 2011), and calculate the EMV linguistically, which is more appropriate in the construction domain. The proposed framework provides risk analysts with the ability to conduct event-tree analysis even if data are not available. In addition, experts are offered the ability to track the calculated EMV of risk events and verify the results. Using the proposed framework, risk response strategies can be analyzed, and cost-efficient risk response strategies can be developed by examining options that reduce the chances of failure. Moreover, this paper provides a flexible framework in which membership functions can be calibrated to suit different contexts.

Fuzzy fault-tree and fuzzy event-tree analyses were automated by developing a software package called Fuzzy Reliability Analyzer. Horizontal directional drilling failure to meet project objectives was identified as a critical risk event using the Risk Criticality Analyzer. This risk event was then analyzed using fuzzy fault-tree and fuzzy event-tree analyses. Monte Carlo simulation was conducted and used to validate the results, which indicated that comparable results can be obtained using the proposed framework but with additional advantages.

In this study, standard trapezoidal fuzzy numbers were considered to represent the fuzzy probability of occurrence and impact of different risk events. Future research can be conducted using different shapes of membership functions to compare the results to the findings of this study. Moreover, root causes of critical risk events can be collected in a database and utilized to develop an intelligent system that can automate the generation of fault trees.

Acknowledgments

During this study, a great deal of support was received from many people within Enbridge Pipelines. The authors would like to express their appreciation to Mr. Fernando Martinez and Mr. Amit Aulakh for all the time, effort, and feedback received during this research. This work was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Associate Industrial Research Chair in Construction Engineering and Management at the University of Alberta under a Natural Sciences and Engineering Industrial Research Chair Grant NSERC IRCPJ 349527-05.

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