Fuzzy Reliability Analyzer: Quantitative Assessment of Risk Events in the Construction Industry Using Fuzzy Fault-Tree Analysis

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Abstract: Fault trees are deductive techniques constructed by taking a system failure event and deconstructing it into its root causes (basic events, gate events). Fault trees can be solved qualitatively, by determining minimal cut sets, and quantitatively, by calculating the probability of occurrence of the risk event. In conventional fault-tree analysis (FTA), the probability of occurrence for all basic events must be assessed in order to allow for quantitative fault-tree analysis. However, conducting quantitative fault-tree analysis, especially in construction projects, entails several difficulties owing to the lack of sufficient data, leading to an approximation of the probability of occurrence for some basic events. Assuming probabilities for any basic event will add further uncertainty to the analysis, resulting in a potentially questionable end result. To overcome the challenge of assessing probabilities, this paper presents a comprehensive framework in which experts can use linguistic terms rather than numerals to assess the probability of occurrence of basic events. Fuzzy arithmetic operations are used to perform quantitative fault-tree analysis. Fuzzy Reliability Analyzer (FRA) was developed to automate both qualitative and quantitative FTA. The method presented is demonstrated via a case study to quantify the probability of failure of horizontal directional drilling (HDD) in meeting project objectives. Fourteen minimal cut sets were identified and the fuzzy probability (FPro) of the top event (TE) was calculated. The proposed approach offers the advantage of allowing experts to express themselves linguistically to assess the probability of occurrence of basic events, which is more appropriate for the construction domain. In addition, the proposed method offers the risk analyst the advantage of ranking basic events according to their level of contribution to the probability of the risk event, which can help in establishing more effective risk response strategies. **DOI: 10.1061/(ASCE)CO.1943-7862.0000285.** © *2011 American Society of Civil Engineers.*

CE Database subject headings: Risk management; Probability; Fuzzy sets; Reliability; Construction industry.

Author keywords: Risk management; Probability; Fuzzy sets; Reliability.

Introduction

A fault tree (FT) is a structured logical diagram that is constructed by decomposing internal and external root causes (basic events, gate events), that, if they occur on their own or in a combination (i.e., cut sets), will prompt the top event (i.e., risk event). 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 recognize the advantages of FTA, and in 1966 it developed a simulation program for the evaluation of multiphase fault trees (Ericson 1999). Following the advancement of using FTA in the aerospace industry, the technique began to gain widespread acceptance among practitioners in the nuclear industry. Since then, significant contributions have been made in advancing FTA by developing algorithms and software to solve fault trees (Ericson 1999).

Fault trees are currently used within many industries for conducting qualitative and quantitative assessment of risk events. Qualitative FTA is used to transform the logical relationship between the top event (risk event) and basic events into mathematical equations, known as minimal cut sets (MCS), by applying Boolean algebra. Ayyub (2003) defined a minimal cut set as "a cut set with the condition that the nonoccurrence of any one basic event from this set results in the nonoccurrence of the top event." Qualitative FTA can be used to help in understanding how a risk event may occur, by reviewing different minimal cut sets, and later will be explained in more detail. Fault trees can also be used for quantitative risk assessment by determining the probability of occurrence of the top event (risk event). The probability of the top event (TE) is calculated by assigning values to the probability of basic events and propagating the calculations of the probabilities, using Boolean algebra, until the TE is reached. To do so, enough historical data are required to estimate the probability of basic events; however, having sufficient data to derive probability distributions is often difficult in construction industry.

This paper presents a more realistic approach for the construction industry to conduct fault-tree analysis by applying fuzzy logic rather than probability theory for quantitative FTA. The proposed approach is intended to overcome the drawbacks of applying probability theory to conduct quantitative FTA. Using the proposed approach, the probability of basic events is defined using possibility distributions rather than probability distributions. Experts can provide linguistic assessments, rather than numerical values, to

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Note. This manuscript was submitted on November 10, 2009; approved on August 22, 2010; published online on September 2, 2010. Discussion period open until September 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 137, No. 4, April 1, 2011. ©ASCE, ISSN 0733-9364/2011/4-294–302/$25.00.

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assess the probability of occurrence of basic events, which are referred to as fuzzy probabilities (FPro). Each linguistic assessment for each basic event (BE) is represented using alpha cuts. Fuzzy arithmetic operations are applied thereafter to conduct quantitative FTA. Sensitivity analysis is conducted to rank different basic events according to their level of contribution to the fuzzy probability of the TE (risk event).

The proposed approach is used to conduct quantitative FTA in the construction industry, as illustrated using a case study to quantify the probability of failure of horizontal directional drilling (HDD) in meeting the project objectives. The proposed approach offers risk analysts with the advantage of using linguistic terms to assess risk events, which is more appropriate for the construction industry. By ranking different basic events, risk analysts can identify the most significant basic events that contribute to the occurrence of risk events, in order to develop better risk response strategies to address these basic events. Thus, more cost efficient risk response strategies can be developed by allocating resources to the root causes that have the most significant contribution to the occurrence of risk events.

Fault Trees

Fault trees have a basic structure similar to the one shown in Fig. 1. The TE in any fault tree is the failure event (risk event) and it is decomposed into its root causes. Basic events represent the lowest level of each branch in the fault tree, which can not be further developed. The TE is usually connected logically to basic events through gate events (GEs); however, the TE can, in some cases, also be directly connected to BEs. GEs are similar to the TE in that they can be further decomposed to their root causes. The most commonly used logic to connect events (basic events, gate events) in any fault-tree structure is AND (∩) and OR (∪) gates. The AND gate is used to represent the logic that the upper event cannot occur unless all the lower events occur (i.e., intersection). The OR gate is used to represent the logic that the occurrence of any single event in the lower level is sufficient for the upper event to occur (i.e., union).

Conventional Fault-Tree Analysis

The construction of fault trees is a major task and requires the participation of subject matter experts from several disciplines. The participation of these experts is essential in order to identify the correct cause and effect logic. After constructing fault trees, risk analysts can perform qualitative FTA to obtain MCS. The traditional approach to obtain MCS is to perform Boolean algebra. The analysis can be performed using one of two approaches: either top down or bottom up. In the top-down approach, the analysis starts from the TE and moves down until reaching basic events. The bottom-up approach starts from basic events and moves up until reaching the TE. Applying either the top-down approach or the bottom-up approach will lead to the same minimal cut sets.

To demonstrate the calculations of MCS, the structure shown in Fig. 1 is used to apply the top-down approach for obtaining MCS as shown in Eqs. (1) to (6):

$$\mathrm{TE} = \mathrm{GE}_1 \cup \mathrm{GE}_2 \cup \mathrm{GE}_3 \tag{1}$$

$$\mathrm{GE}_1 = \mathrm{BE}_1 \cap \mathrm{BE}_2 \tag{2}$$

$$\mathrm{GE}_2 = \mathrm{BE}_1 \cup \mathrm{BE}_3 \cup \mathrm{BE}_4 \tag{3}$$

$$\mathrm{GE}_3 = \mathrm{BE}_5 \cap \mathrm{BE}_6 \cap \mathrm{BE}_7 \cap \mathrm{BE}_8 \tag{4}$$

$$\mathrm{TE} = (\mathrm{BE}_1 \cap \mathrm{BE}_2) \cup \mathrm{BE}_1 \cup \mathrm{BE}_3 \cup \mathrm{BE}_4 \cup (\mathrm{BE}_5 \cap \mathrm{BE}_6 \cap \mathrm{BE}_7 \cap \mathrm{BE}_8) \tag{5}$$

$$M_1 = (\mathrm{BE}_1, \mathrm{BE}_2); \quad M_2 = (\mathrm{BE}_1); \quad M_3 = (\mathrm{BE}_3); \quad M_4 = (\mathrm{BE}_4); \quad M_5 = (\mathrm{BE}_5, \mathrm{BE}_6, \mathrm{BE}_7, \mathrm{BE}_8) \tag{6}$$

where M_1, M_2, M_3, M_4, and M_5 = minimal cut sets.

Eq. (6) shows that there are five minimal cut sets. M_1 indicates that BE_1 and BE_2 must occur together to cause the TE to occur. M_2, M_3, and M_4 indicate that BE_1, BE_3, and BE_4, respectively, are critical basic events, because each one is sufficient by itself to cause the TE to occur. M_5 indicates that BE_5, BE_6, BE_7, and BE_8 must occur together to cause the TE to occur. Following the creation of the MCS, Boolean simplifications are conducted according to the standard Boolean rules shown in Table 1. In this example, BE_1 is a repeated basic event (RBE), because it appears in both M_1 and M_2, and is simplified by applying the absorption law as follows:

$$(\mathrm{BE}_1 \cap \mathrm{BE}_2) \cup \mathrm{BE}_1 = \mathrm{BE}_1 \tag{7}$$

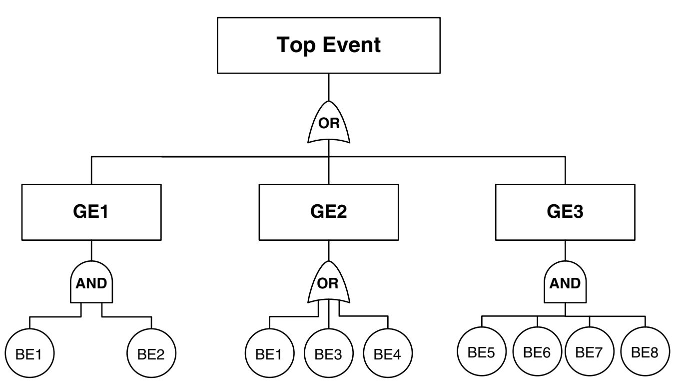

Fig. 1. Example of fault-tree structure

Table 1. Boolean Algebra Rules (Adapted from NASA 2002)

Law	Rule 1	Rule 2
Commutative	$x \cap y = y \cap x$	$x \cup y = y \cup x$
Associative	$x \cap (y \cap z) = (x \cap y) \cap z$	$x \cup (y \cup z) = (x \cup y) \cup z$
Distributive	$x \cap (y \cup z) = (x \cap y) \cup (x \cap z)$	$x \cup (y \cap z) = (x \cup y) \cap (x \cup z)$
Idempotent	$x \cap x = x$	$x \cup x = x$
Absorption	$x \cap (x \cup y) = x$	$x \cup (x \cap y) = x$
Transitivity	If $x \subset y$ and $y \subset z$, then $x \subset z$	
Involution	$\bar{\bar{x}} = x$	
Boundary conditions	$x \cap \emptyset = \emptyset$ $x \cup \emptyset = x$	$x \cap X = x$ $x \cup X = X$
De Morgan's theorem	$(x \cup y)^- = \bar{x} \cap \bar{y}$	$(x \cap y)^- = \bar{x} \cup \bar{y}$
Complementation	$x \cap \bar{x} = \emptyset$	$x \cup \bar{x} = X$

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Thus, Eq. (5) can be further simplified as follows:

$$T = \mathrm{BE}_1 \cup \mathrm{BE}_3 \cup \mathrm{BE}_4 \cup (\mathrm{BE}_5 \cap \mathrm{BE}_6 \cap \mathrm{BE}_7 \cap \mathrm{BE}_8) \quad (8)$$

Eq. (8) shows the results after conducting qualitative FTA and can be used to understand and explain how different basic events are connected logically to cause the TE to occur. After identifying the minimal cut sets, the probability of the TE or GEs connected by an OR gate is defined as shown in Eq. (9) for mutually exclusive events (Singer 1990):

$$\Pr(\mathrm{TE}) = 1 - \prod_{i=1}^{N}(1 - \mathrm{MCS}_i) \quad (9)$$

where N = total number of MCS; and Pr = probability of occurrence. Event A and event B are mutually exclusive if they cannot both occur simultaneously (i.e., if $A \cap B = \emptyset$).

The probability of the TE or GEs connected by an AND gate is defined as shown in Eq. (10) (Singer 1990):

$$\Pr(\mathrm{TE}) = \prod_{i=1}^{N}(\mathrm{MCS}_i) \quad (10)$$

To illustrate Eqs. (9) and (10), assume that all the basic events connected by an OR gate in Fig. 1 are mutually exclusive and that there are sufficient data to estimate the probability of basic events as follows:

$\Pr(\mathrm{BE}_1) = 0.20$; $\Pr(\mathrm{BE}_2) = 0.25$; $\Pr(\mathrm{BE}_3) = 0.35$; $\Pr(\mathrm{BE}_4) = 0.45$; $\Pr(\mathrm{BE}_5) = 0.35$; $\Pr(\mathrm{BE}_6) = 0.60$; $\Pr(\mathrm{BE}_7) = 0.15$; $\Pr(\mathrm{BE}_8) = 0.10$

The probability of occurrence of the TE is calculated as follows:

$$\Pr(\mathrm{TE}) = 1 - [(1 - 0.20) \times (1 - 0.35) \times (1 - 0.45) \times (1 - 0.35 \times 0.60 \times 0.15 \times 0.10)] = 0.71 \quad (11)$$

For conventional FTA, sufficient data are required to estimate the probability of basic events. In reality, particularly for the construction industry, the assessment of the probability of occurrence of basic events represents the most significant challenge in conducting quantitative FTA, and hence a more practical approach is required. The next section illustrates how fuzzy logic can be used to address this challenge to yield a more realistic and practical approach to facilitate quantitative FTA, suitable for the construction domain.

Fuzzy Fault-Tree Analysis

The concept of fuzzy logic was first suggested by Zadeh (1965). Fuzzy logic can be useful in creating more transparent and intuitive decision-support models that can be developed for any application. Fuzzy logic allows for the gradual transition between different concepts through the use of membership functions (MFs) that represent the linguistic terms describing the concepts. To illustrate, assume that risk experts defined the range of the term "medium probability" using the following crisp set:

$$\text{Medium Probability}\,(x) = \begin{cases} 1 & \text{if } x \in [0.3\; 0.5] \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

Eq. (12) implies that the probability of occurrence of any risk event will be considered medium only if the value is located within the interval [0.3–0.5]. Using this formulation, a probability value of 0.29 would be considered out of the range of medium probability, which does not make sense.

Fuzzy logic can deal with this problem effectively by allowing a gradual transition between different concepts. In this regard, each element in the "medium probability" set is assigned a membership degree (μ), ranging from 0 to 1.0, to express the degree of belief that a certain element corresponds to a certain concept. Each element can have a different membership degree in more than one concept. For instance, in the previous example 0.29 can have a membership degree in the concept of "medium probability" of 0.98 and at the same time a membership degree in the concept of "low probability" of 0.20. By associating each element in a set with a membership degree, the MF for each concept can be established.

Pioneering work on applying fuzzy FTA was done by Tanaka et al. (1983). This concept has been used extensively by several writers in several industries. For example, Huang et al. (2000) applied fuzzy fault trees for safety analysis to assess the probability of traffic accidents in a railway traffic system. Yuhua and Datao (2005) applied a fuzzy fault tree to assess the probability of oil and gas transmission pipeline failure. Pan and Wang (2007) applied fuzzy fault trees to estimate the probability of failure of bridge construction.

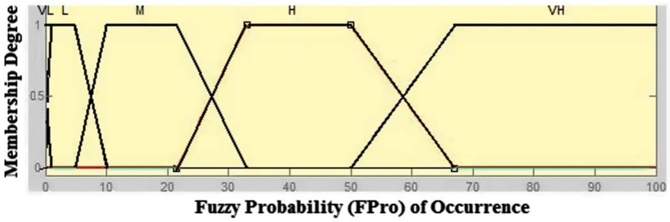
Quantitative FTA is a time-consuming activity and requires several steps. In the proposed approach, the following steps are adopted (Hauptmanns 1988; NASA 2002):

1. Use feedback from experts to construct fault trees.
2. Establish a range of values for each linguistic term used to assess the fuzzy probability of basic events.
3. Use the linguistic terms in step 3 to assess the fuzzy probability for all basic events.
4. Conduct qualitative FTA by formulating the MCS.
5. Conduct quantitative FTA by calculating the TE fuzzy probability.
6. Conduct sensitivity analysis by means of fuzzy importance analysis.
7. Analyze the results from steps 4, 5, and 6 and use them to develop risk response strategies.

Steps 1 and 3 rely on the elicitation of knowledge from experts using any standard technique (e.g., Chapman 1998). The next sections highlight steps 2, 4, 5, 6, and 7.

Step 2: Establish Range of Values to Assess the Fuzzy Probability of Basic Events

To define the linguistic terms to assess the fuzzy probability of occurrence of basic events, an interview was arranged with a senior risk coordinator working at one of the largest pipeline companies in North America. The interview started by reviewing the approach used by the company to assess the probability of occurrence of risk events as defined in the company risk management standard. They use five linguistic terms [very low (VL), low (L), medium (M), high (H), and very high (VH)] to assess the probability of occurrence. The same expert was consulted to establish the membership function for each linguistic term. The direct method with one expert (Klir and Yuan 1995) was used to elicit the required information to build the membership function for each linguistic term. Fig. 2 shows the results of this elicitation process, which represent the fuzzy probability (FPro) of occurrence of basic events. The range of each linguistic term can be calibrated to suit a different organization or context simply by reeliciting the values for the MFs defining each linguistic term.



Linguistic Term	Trapezoidal Representation (a,b,c,d)			
	a	b	c	d
VL	0	0	0	1
L	0	1	5	10
M	5	10	21.5	33
H	21.5	33	50	67
VH	50	67	100	100

Fig. 2. Membership functions for FPro of occurrence of basic events

Step 4: Qualitative Fault-Tree Analysis

Qualitative FTA is conducted to obtain MCS, which can be performed manually as shown in Eqs. (1)–(6). However, manual calculation of MCS is a tedious and time-consuming job, particularly for large fault trees. Several attempts have been made to automate the calculation of minimal cut sets (e.g., Hauptmanns 1988; Vatn 1992; Kara-Zaitri 1996; Rosenberg 1996; Carrasco and Suñé 1999). In the proposed approach, Hauptmanns' algorithm (1988) is used because it is intuitive, can create MCS for any fault-tree structure, and can be easily automated. In order to automate the algorithm, the following steps are applied (Hauptmanns 1988):

1. Transform the fault-tree logic into a Boolean matrix (BM) composed of 0's and 1's. "0" is used to indicate that no connection exists, whereas "1" is used to indicate a connection between events. The rows of the BM are divided into two sections: the "OR" GEs in the upper part and the "AND" GEs in the lower parts. The columns of the BM are divided into three blocks starting with basic events, followed by "OR" GEs, and finally followed by "AND" GEs.
2. Create another empty matrix, referred to as the working Boolean matrix (WBM), and start the analysis from the TE.
3. Replace the TE in the WBM with it is equivalent (basic events/gate events) from the Boolean Matrix, referred to as the connection list (CL), by taking the following two rules into consideration:
   a. If the TE is connected by an "OR" gate with its CL, then insert each event from the CL into a separate row in the WBM.
   b. If the TE is connected by an "AND" gate with its CL, then insert all the events from the CL into a single row in the WBM. Table 2 shows the WBM after applying step 3 to the fault-tree structure shown in Fig. 1. As shown in Table 2, because the TE in the BM, is connected by "1" with three gate events (GE1, GE2, GE3) using an "OR" gate, the WBM is created by inserting three separate rows, applying rule 3a, and adding a connection "1" under each gate event.
4. Scan all the rows of the WBM to check if there is any connection "1" under any of the two blocks named "OR (GE)" and "AND (GE)". If so, then replace each gate event in the WBM with its equivalent (basic events/gate events) from the BM,

Table 2. Initial Working Boolean Matrix Representation of Example Fault Tree

Basic events								OR (GE)		AND (GE)	
BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8	TE	GE2	GE1	GE3
0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	1

Table 3. Final Working Boolean Matrix of Example Fault Tree

Basic events								OR (GE)		AND (GE)	
BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8	TE	GE2	GE1	GE3
1	1	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	0	0	0	0

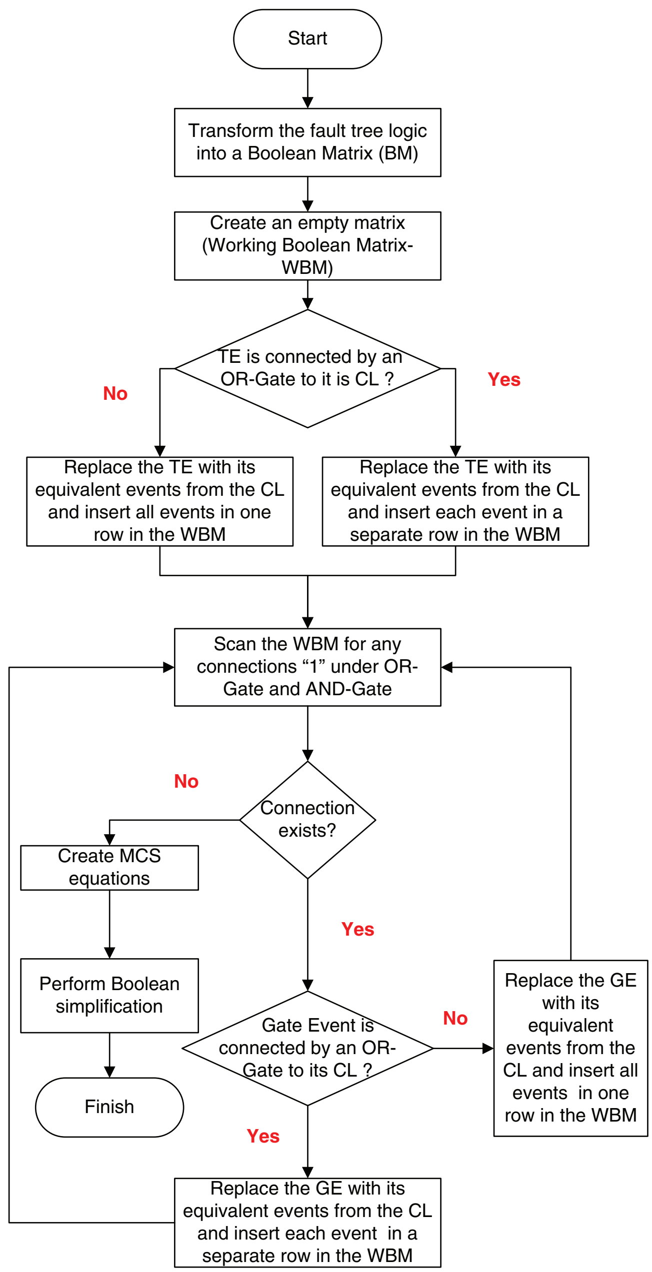


Fig. 3. Flowchart of Hauptmanns' algorithm

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referred to as the CL, by taking the following two rules into consideration:

a. If a gate event is connected by an "OR" gate with its CL, then insert each event from the CL into a separate row in the WBM.
b. If a gate event is connected by an "AND" gate with its CL, then insert all the events from the CL into a single row in the WBM.

5. Repeat step 4 until the WBM contains "0" connections in the last two blocks, "OR (GE)" and "AND (GE)." Table 3 shows the final WBM for the example fault tree.
6. Use each row in the final WBM to develop the MCS equations by converting each connection "1" in a row with its related basic event, and connect basic event(s) within each row using intersection "∩." For example, the first row in Table 3 can be read as "$BE_1 \cap BE_2$." Basic event(s) in a row is/are connected with basic event(s) in another row using the union "∪" operator. For example, the first and the second rows in Table 3, can be read as $BE_1 \cap BE_2 \cup BE_1$. By applying step 6 to all the rows in Table 3, a similar result to Eq. (5) is obtained.
7. Perform Boolean simplifications on the MCS equations. Fig. 3 shows a flowchart of the algorithm presented in this step.

Step 5: Quantitative Fault-Tree Analysis

Quantitative FTA is conducted by calculating the TE probability. In the proposed approach, the probability of occurrence of each basic event is assessed linguistically by selecting one of the linguistic terms [i.e., membership functions (MFs)] presented in Fig. 2.

Each of the MFs presented in Fig. 2 is represented using the alpha cut (α cut) principle. 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 argument. Fuzzy arithmetic operations are then utilized to convert the "OR" and "AND" gates as follows:

The α cut of the fuzzy probability of a TE or gate event connected by an OR gate is defined as shown in Eq. (13) (Verma et al. 2007) for mutually exclusive events using trapezoidal fuzzy numbers:

$$\mathrm{FPro\,(TE)}^{\alpha} = \left\{1 - \prod_{i=1}^{n}[1-(a_i+(b_i-a_i))^{\alpha}],\; 1-\prod_{i=1}^{n}[1-(d_i-(d_i-c_i))^{\alpha}]\right\} \tag{13}$$

where n = number of MCS connected by OR; a = minimum value; b and c = most likely value; and d = maximum value of the MF, as illustrated in Fig. 2.

The fuzzy probability of a TE or gate event connected by an AND gate is defined as shown in Eq. (14) (Verma et al. 2007).

$$\mathrm{FPro(Top\ Event)}^{\alpha}\left\{\prod_{i=1}^{s}[a_i+(b_i-a_i)^{\alpha}],\prod_{i=1}^{s}[d_i-(d_i-c_i)^{\alpha}]\right\} \tag{14}$$

where s = number of MCS connected by AND; and a, b, c, and d are defined as in Eq. (13).

The multiplication operator, $\prod$, in Eqs. (13) and (14) is defined as follows:

If A and B are two fuzzy sets represented over the interval $A^{\alpha}=[a_1 d_1]$, $B^{\alpha}=[a_2 d_2]$, then $A^{\alpha} * B^{\alpha}$ is defined as shown in Eq. (15) (Verma et al. 2007):

$$A^{\alpha}\times B^{\alpha} = [\min(a_1\times a_2, a_1\times d_2, d_1\times a_2, d_1\times d_2),\; \times\max(a_1\times a_2, a_1\times d_2, d_1\times a_2, d_1\times d_2)] \tag{15}$$

The example fault tree presented in Fig. 1 is used to illustrate Eqs. (13)–(15). It is assumed that a risk assessment workshop was arranged with experts to provide an assessment of the probability of basic events according to the linguistic terms established in Fig. 2, and that the following results were obtained: $\mathrm{FPro(BE_1)} = \mathrm{Medium}$; $\mathrm{FPro(BE_2)} = \mathrm{Medium}$; $\mathrm{FPro(BE_3)} = \mathrm{Medium}$; $\mathrm{FPro(BE_4)} = \mathrm{High}$; $\mathrm{FPro(BE_5)} = \mathrm{Medium}$; $\mathrm{FPro(BE_6)} = \mathrm{High}$; $\mathrm{FPro(BE_7)} = \mathrm{Low}$; $\mathrm{FPro(BE_8)} = \mathrm{Low}$

By applying Eqs. (13) and (14), the fuzzy probability of the TE is written as follows:

$$\mathrm{FPro(TE)}^{\alpha} = 1-\{[1-\mathrm{FPro(BE_1)}^{\alpha}]\times[1-\mathrm{FPro(BE_3)}^{\alpha}] \times[1-\mathrm{FPro(BE_4)}^{\alpha}]\times[1-\mathrm{FPro(BE_5)}^{\alpha} \times\mathrm{FPro(BE_6)}^{\alpha}\times\mathrm{FPro(BE_7)}^{\alpha}\times\mathrm{FPro(BE_8)}^{\alpha}]\} \tag{16}$$

Eq. (16) is used to calculate the TE fuzzy probability by incrementally increasing the value of alpha by 0.05 increments. For instance, at α equals zero, Eq. (16) can be written as follows:

$$\mathrm{FPro}(X)^0 = (\{1-[0.05+(0.1-0.05)]\},\{1-[0.33-(0.33-0.215]\})\times(\{1-[0.05+(0.1-0.05)]\},\{1-[0.33-(0.33-0.215)]\}) \times(\{1-[0.215+(0.33-0.215)]\}),\{1-[0.67-(0.67-0.50)]\}) \tag{17a}$$

$$\mathrm{FPro(TopEvent)}^0 = 1-\{\mathrm{FPro}(X)^0\times[1-(\{[0.05+(0.1-0.05)],[0.33-(0.33-0.215)]\} \times\{[0.215+(0.33-0.215)],[0.67-(0.67-0.50)]\}\times\{[0+(0.01-0)],[0.10-(0.10-0.05)]\})]\} \tag{17b}$$

By using Eq. (15) to solve the multiplication operator in Eq. (17), the fuzzy probability of occurrence of the TE at alpha equals zero is calculated as follows:

$$\mathrm{FPro(TE)}^0 = [29.15\;85.22] \tag{18}$$

By substituting the fuzzy probability of basic events into Eq. (16) for different α cuts, the fuzzy probability of occurrence of the TE can be calculated as shown in Fig. 4.

To provide a crisp value of the fuzzy probability of occurrence for the TE (risk event), the mean of maximum (MOM) method is selected for defuzzification. The MOM represents the average value of the maximum fuzzy probability at which the MF reaches a value of 1. Because the membership function at $\alpha = 1$ represents the most confident level, the mean of maximum can be viewed as the average of the most likely estimate of probability over the most confident range. Eq. (19) shows the defuzzified estimate of the TE fuzzy

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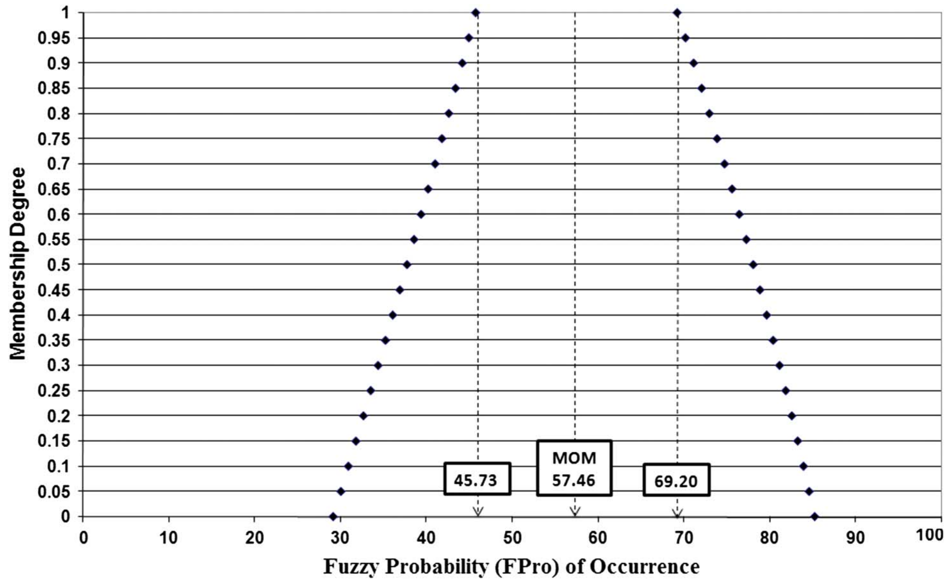

Fig. 4. Fuzzy probability of TE (risk event) for example fault tree

probability of occurrence using the MOM method, as shown in Fig. 4:

$$\mathrm{FPro(TE)}^0 = \left(\frac{45.73 + 69.20}{2}\right) = 57.46\% \tag{19}$$

Step 6: Fuzzy Importance Analysis

Determining the importance level of different root causes is essential for complete FTA. In previous FTA studies, results show that less than 20% of basic events in a fault tree are responsible for more than 90% of the probability of the TE (NASA 2002). In the probability domain, several measures have been developed to rank root causes [e.g., Fussell-Vesely importance, risk reduction worth, Birnbaum's importance (Vesely et al. 1983)]. In the fuzzy domain, several fuzzy importance techniques have been developed. The basis of these techniques is to first assess the TE fuzzy probability (TE_1), assuming that all basic events will occur according to their respective fuzzy probability. Next, each basic event is eliminated in turn (i.e., by setting FPro $= 0$ for the basic event) and again calculating the TE fuzzy probability (TE_2). Suresh et al. (1996) introduced a fuzzy importance measure (FIM) by calculating the Euclidean distance (ED) [TE_1 TE_2] between TE_1 and TE_2. Khan and Abbasi (1999) utilized a different fuzzy importance measure calculated as follows:

$$\mathrm{FIM} = \left[\frac{\mathrm{TE}_1 - \mathrm{TE}_2}{\mathrm{TE}_1}\right] \times 100\% \tag{20}$$

Because there is no way to judge whether one FIM is better than another without testing, both fuzzy importance measures were used and the results reviewed with the same senior risk coordinator. The results showed that the FIM utilized by Khan and Abbasi (1999) [Eq. (20)] gives more logical results, based on the risk coordinator's assessment. The FIM is illustrated in the case study presented later in the paper.

Step 7: Analyze the Results to Develop Risk Response Strategies

The MCS generated from qualitative FTA can help to understand the logical combinations between different root causes that can lead to the occurrence of the risk event. Risk analysts can use MCS to communicate the logic behind the occurrence of the risk event to different team members. Accordingly, proactive risk response strategies can be designed to control the identified root causes at early stages before the risk event is realized.

Fuzzy Reliability Analyzer

To automate the qualitative and quantitative fuzzy FTA, a software package called Fuzzy Reliability Analyzer (FRA) was developed in visual basic (VB.net). FRA is composed of seven modules. The function of each module is as follows:

1. Fuzzy probability identification module: this is used to define the MFs for different linguistic terms using a trapezoidal representation. To calibrate the MFs, expert(s) can be consulted to define the four point representation of the trapezoidal functions for different linguistic terms.
2. Data input module: this is used to collect data to establish the fault-tree logic and to support FTA. Inputs include: basic event ID, basic event description, basic event fuzzy probability, gate event ID, gate event description, TE description, and gate type (OR/AND).
3. Data integrity check module: this performs several integrity checks on the data provided by the user.
4. Minimum cut set generator module: this creates the BM and the WBM by applying Hauptmanns' algorithm (1988). Summary results are presented to the user on the FRA screen under the section called "FTA-Qualitative Analysis" (shown in Fig. 5). Detailed calculations of BM and WBM are exported to Excel.
5. Boolean algebra simplification module: this is triggered only if the fault tree contains RBE. FRA interacts with MuPAD from the symbolic math toolbox, running under the Mathlab environment, to perform Boolean simplification.
6. Quantitative FTA module: this generates alpha cuts and performs quantitative FTA according to Eqs. (13)–(15). The

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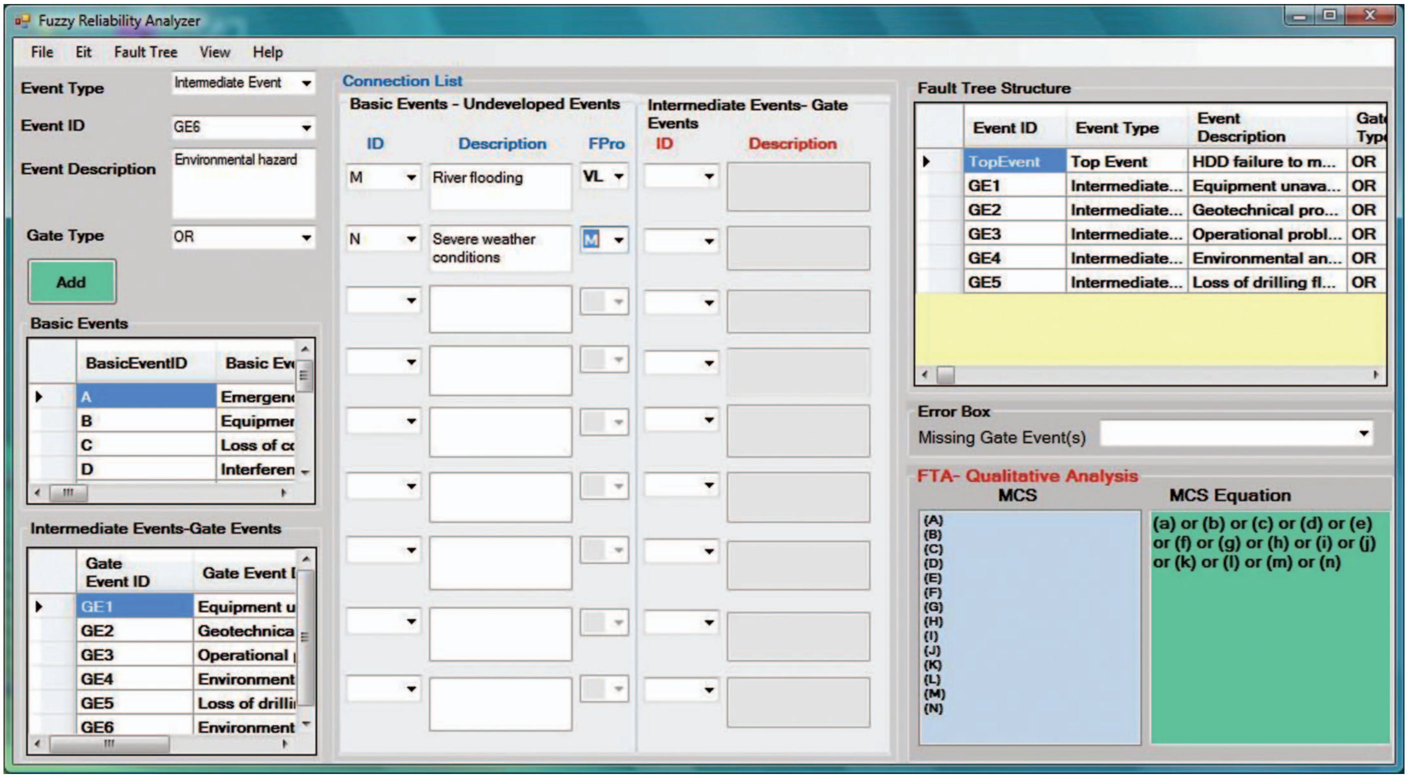

Fig. 5. FRA qualitative FTA for HDD case study

results of the analysis are presented to the user in an Excel spreadsheet.

7. Fuzzy importance analysis module: this is used to measure the level of importance of different basic events according to their level of contribution to the probability of occurrence of the TE. FRA was coded to handle up to 26 basic events, which is sufficient to demonstrate the concept. Future coding can be incorporated to handle more basic events.

Case Study to Illustrate Fuzzy Fault-Tree Analysis

To verify the validity of using fuzzy logic to provide quantitative FTA in the construction domain, horizontal directional drilling (HDD) was selected as a case study. HDD was selected as a case study because of its complexity and criticality, where several independent root causes can interact to cause failure. Any pipeline project may contain several HDD crossings at different locations, and the failure of any of these HDD crossings can lead to substantial cost overruns on the project. Thus, it is essential to identify the critical HDD crossings, and start as early as possible to look for risk response strategies. It is important to note that each HDD crossing is unique, and hence the ability to collect data regarding some root causes is difficult, if not impossible, which makes quantitative FTA of such fault trees not possible using probability theory.

To establish the fault-tree structure for the selected HDD crossing, several interviews were arranged with the senior risk coordinator and another risk engineer working in the collaborating pipeline company. The Delphi technique was used to reach consensus between the two experts' opinions. First, the risk engineer was interviewed to establish the structure of the fault tree. The risk engineer reviewed fault tree was then presented to the senior risk coordinator for feedback. Modifications as recommended by the senior risk coordinator were then presented to the risk engineer for further review and feedback. The risk engineer noted his agreement with the fault-tree structure. The TE was identified as HDD failure to meet project objectives of cost and time. All root causes were identified, connected using AND/OR gates, as shown in Fig. 6 (Abdelgawad et al. 2010), and assessed by both experts according to the criteria established in Fig. 2. Table 4 shows the different basic events and their linguistic assessment (Abdelgawad et al. 2010). FRA is used to conduct qualitative and quantitative FTA of the fault tree. The qualitative assessment of the fault tree yields 14 MCS (A to N), as shown in Fig. 5. The fuzzy probability of occurrence of the TE (risk event) is written as follows:

$$\begin{aligned}\mathrm{FPro(Top\ Event)}^{\alpha} = 1 - [&(1-\mathrm{FPro(A)}^{\alpha}) * (1-\mathrm{FPro(B)}^{\alpha})\\ &* (1-\mathrm{FPro(C)}^{\alpha}) * (1-\mathrm{FPro(D)}^{\alpha}) * (1-\mathrm{FPro(E)}^{\alpha})\\ &* (1-\mathrm{FPro(F)}^{\alpha}) * (1-\mathrm{FPro(G)}^{\alpha}) * (1-\mathrm{FPro(H)}^{\alpha})\\ &* (1-\mathrm{FPro(I)}^{\alpha}) * (1-\mathrm{FPro(G)}^{\alpha}) * (1-\mathrm{FPro(K)}^{\alpha})\\ &* (1-\mathrm{FPro(L)}^{\alpha}) * (1-\mathrm{FPro(M)}^{\alpha}) * (1-\mathrm{FPro}(N)^{\alpha})]\end{aligned} \quad (21)$$

By substituting the fuzzy probability of basic events into Eq. (21) for different α cuts and applying the MOM defuzzification, FRA calculates the fuzzy probability of the TE as 78.54%.

FRA is also used to conduct fuzzy importance analysis, as shown in Table 5. The qualitative FTA shows that each basic event by itself is sufficient to cause the TE to occur, and represents a critical cause and effect logic. The results in Table 5 indicate that altering basic event A can reduce the probability from 78.54% to 65.68%. Altering basic event B can reduce the probability from 78.54% to 75.42%. The same concept can be applied to interpret the rest of the results presented in Table 5. Results from FIM also show that the emergency shutdown system trips [basic event (A)] is ranked first in contributing to the TE fuzzy probability. In this

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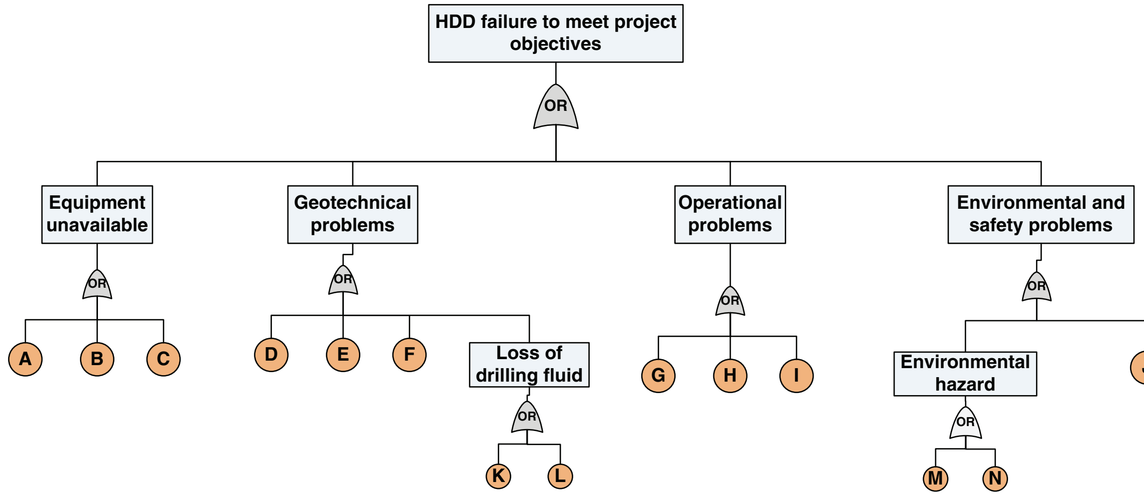

Fig. 6. Fault-tree diagram for HDD failure to meet project objectives (Abdelgawad et al. 2010, ASCE)

Table 4. Basic Events and Fuzzy Probability Assessment for HDD Case Study (Abdelgawad et al. 2010, ASCE)

Symbol	Description	FPro of occurrence
A	Emergency shutdown system trips	High (H)
B	Equipment breakdown	Medium (M)
C	Loss of communication with drilling machine	Low (L)
D	Interference with bedrock	Medium (M)
E	Interference with aquifer	Medium (M)
F	Unstable bank	Medium (M)
G	Operator lacking required skills	Low (L)
H	Fatigue of workers	Very low (VL)
I	Lack of proper supervision	Low (L)
J	Safety incidents on site	Low (L)
K	Seepage of drilling fluid into waterway	Low (L)
L	Seepage of drilling fluid into soil	Medium (M)
M	River flooding	Very low (VL)
N	Severe weather conditions	Medium (M)

Table 5. Fuzzy Importance Analysis for HDD Case Study

Event ID	TE_1	TE_2	FIM	Rank
A	78.54	65.68	16.37	1
B	78.54	75.42	3.97	2
C	78.54	78.13	0.52	3
D	78.54	75.42	3.97	2
E	78.54	75.42	3.97	2
F	78.54	75.42	3.97	2
G	78.54	78.13	0.52	3
H	78.54	78.54	0	4
I	78.54	78.13	0.52	3
J	78.54	78.13	0.52	3
K	78.54	78.13	0.52	3
L	78.54	75.42	3.97	2
M	78.54	78.54	0	4
N	78.54	75.42	3.97	2

example, a risk response strategy can be established by incorporating the evaluation of the reliability of the HDD contactor's equipment within the prequalification strategy.

"Face validation" was used to check the validity of the findings (Lucko and Rojas 2010). An interview was conducted with both experts to review the results obtained from FRA, including the TE fuzzy probability and the outcomes of fuzzy importance analysis. Given their previous experience with the failure of HDD during the construction phase and the difficulty of assessing the probability of basic events using numerical inputs, both experts agreed with the findings of FRA and also indicated the suitability of using linguistic terms to conduct FTA as compared to the conventional approach.

Fuzzy FTA was applied using one risk event to demonstrate the concept. The same technique can be applied to assess different risk events in a construction project by using an appropriate risk register template to collect information from relevant experts, and then applying each of the steps outlined in this paper.

Conclusions and Future Research

In this paper, the concept of fuzzy FTA was investigated and used to quantify the fuzzy probability of HDD failure to meet project objectives. The approach presented in this paper offers the contribution of combining fuzzy logic with fault trees in a comprehensive framework that provides a practical and thorough approach for quantitative FTA, suitable for the construction domain. Risk experts can express the probability of occurrence of basic events linguistically, and these linguistic terms can be calibrated to suit different organizations or contexts. In addition, the framework presented in this paper can be used to understand the logic that can lead to the occurrence of a risk event, and to identify critical root causes by analyzing the level of importance of each basic event in contributing to the fuzzy probability of occurrence of the TE. Using such an approach, the project team can work on establishing proactive risk response strategies to minimize the critical root causes. Thus, more cost-efficient risk response strategies can be established, in which resources and efforts are allocated according to the level of importance of different root causes. The qualitative and quantitative FTAs and the fuzzy importance analysis were automated by developing a software package called the FRA. A case study of horizontal directional drilling was used to illustrate the fuzzy FTA approach. "Face validation" was conducted to validate the

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results. The results demonstrate the suitability of using this technique in the construction domain to conduct quantitative FTA.

Further research is currently in progress to combine fault trees and event trees to estimate the expected monetary value of risk events. Both the fault trees and event trees will be solved using linguistic terms, rather than numerical values. In addition to assessing the fuzzy probability of a risk event, fault trees will be used to assess the fuzzy probability of failure of different risk response strategies. The outcomes of using fuzzy FTA will be used to define the fuzzy probability of failure of different branches in an event tree structure. Event trees will be used to assess the risk impact given different scenarios of failure or success of risk response strategies. By solving the event tree, the expected monetary value of risk events will be estimated.

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 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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