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Approach to integrate fuzzy fault tree with Bayesian network

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Abstract

Fuzzy fault tree (FFT) can offer an efficient method of representing the fault causes and handling fuzzy information in the relationships among events. However, FFT cannot incorporate the evidence into the reasoning as Bayesian Network (BN). To overcome the disadvantage of FFT and BN, an approach of integrating FFT with BN is proposed in this paper. Firstly, the FFT technique of Takagi and Sugeno model that can handle uncertainties in the relationships among different events is introduced. Secondly, the translation rules of converting FFT into BN are presented. The integration algorithm is then demonstrated on an offshore fire case study.

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Keywords: Fuzzy fault tree (FFT); Bayesian Network (BN); fuzzy analytical hierarchy process (FAHP); Fuzzy numbers

1. Introduction

In traditional fault tree analysis (FTA), the probabilities of basic events are treated as exact values, which could not reflect real situation of system because of ambiguity and imprecision of some basic events. In many circumstances, it is generally difficult to estimate the precise probabilities of basic events. Thus, it is often necessary to develop a new method to capture the imprecision of failure data. In this regard, it may be more appropriate to use fuzzy numbers instead of exact probability values [1]. The earliest work in fuzzy fault tree (FFT) treated possibilities of basic events as trapezoidal fuzzy numbers and applied the fuzzy extension principle to determine the occurrence probability of top event [2]. Singer also worked on this area by analyzing fuzzy reliability using standard approximations for the membership functions [3]. However, existing FFT methods cannot deal with uncertainties in relationships among events. Improvements have to be made to apply fuzzy gate to replace traditional gate.

Fault tree (FT) is entirely deterministic and no evidence can be given without re-evaluating the FT [4]. To overcome the shortcoming of FT, Bobbio et al. proposed the conversion algorithm of transforming FT into BN [5], which is a salutary lesson for the algorithm of transforming FFT into BN in this paper. For BN, the root nodes are ranked in terms of the conditional probability, which reflect the contribution to the probability of the eventual fault [6]. Updating the probability is possible when observation is performed on the system [7]. But BN is unable to determine accurately how the failures jointly cause the undesired fault, which is the advantage of FT [8]. To apply the above advantages of the two methods, FFT is integrated with BN in this paper, for which the probability calculation is more flexible and simpler. The description is organized as follows: In section 2, the method of FFT based on the Takagi and Sugeno model is introduced. Section 3 deals with how to transform FFT to BN. Section 4 carries out the possibility assessment of offshore fire.

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2. Fuzzy Fault Tree Analysis

The conventional gates of FT cannot function very well when there are uncertainties in the relationships among events. To handle this fuzzy information, a new gate based on the Takagi and Sugeno (T–S) model is presented. The failure possibility of the top event can be computed by the T–S model from the fuzzy possibilities of the basic events.

2.1. Takagi and Sugeno model

Takagi and Sugeno (T–S) model includes a set of IF-THEN fuzzy rules, which can be used to describe the relationships among events, leading to the construction of the T–S Gate. Consider the rule 1 of the T–S model [9]: Suppose the possibility magnitude of basic events $X_1, X_2, \ldots, X_n$ and upper event $Y$ are denoted respectively by $(X_1^1, X_1^2, \ldots, X_1^{k_1}), (X_2^1, X_2^2, \ldots, X_2^{k_2}), \ldots, (X_n^1, X_n^2, \ldots, X_n^{k_n})$ and $Y^1, Y^2, \ldots, Y^{k_Y}$, which satisfy the following equations:

\[
\begin{align*}
0 &\leq X_1^1 < X_1^2 < \cdots < X_1^{k_1} \leq 1 \\
0 &\leq X_2^1 < X_2^2 < \cdots < X_2^{k_2} \leq 1 \\
\vdots & \\
0 &\leq X_n^1 < X_n^2 < \cdots < X_n^{k_n} \leq 1 \\
0 &\leq Y^1 < Y^2 < \cdots < Y^{k_Y} \leq 1
\end{align*}
\]

Then the T–S gate can be represented by the following fuzzy rules,

\[
\text{Rule } l \ (l = 1, 2, \ldots, m):
\begin{align*}
\text{If } X_1 &\text{ is } X_1^{i_1}, \text{ and } X_2 \text{ is } X_2^{i_2}, \ldots, \text{ and } X_n \text{ is } X_n^{i_n}, \text{ then the possibility of } Y &= P_l(Y^1), Y^2 = P_l(Y^2), \ldots, Y^{k_Y} = P_l(Y^{k_Y}). \\
\end{align*}
\]

“AND” “OR” gates in FTA can be implemented by T–S gate. “AND” gate can be represented by the following fuzzy rule:

\[
\text{If } X_1 \text{ is } 1, \text{ and } X_2 \text{ is } 1, \ldots, \text{ and } X_n \text{ is } 1, \text{ then the possibility of } Y^1 = 0, Y^2 = 0, \ldots, \text{ the possibility of } Y^{k_Y} = 1 \text{ is } 1
\]

Whilst the “OR” gate can be represented by the following fuzzy rules:

\[
\text{Rule } l \ (l = 1, 2, \ldots, m): \text{If } X_1 \text{ is } 1, \text{ then the possibility of } Y^1 = 0, Y^2 = 0, \ldots, \text{ the possibility of } Y^{k_Y} = 1 \text{ is } 1
\]

First of all, to obtain fuzzy rules, the possibility magnitude of basic events should be defined according to historical data and experts’ experience. After that, the fuzzy failure possibilities of top event can be estimated using fuzzy logic. Suppose the possibility of basic event is $X' = (X_1', X_2', \ldots, X_n')$, possibility of top event can be obtained by the T–S gate [10],

\[
\begin{align*}
P(Y^1) &= \sum_{l=1}^{m} \beta_l^1(X') P_l(Y^1) \\
P(Y^2) &= \sum_{l=1}^{m} \beta_l^2(X') P_l(Y^2) \\
P(Y^k) &= \sum_{l=1}^{m} \beta_l^k(X') P_l(Y^k)
\end{align*}
\]

\[
\beta_l^i(X') = \frac{\prod_{j=1}^{n} \mu(X_j')^{i_j}}{\sum_{l=1}^{m} \prod_{j=1}^{n} \mu(X_j')^{i_j}} \quad \text{and } \mu(X_j') \text{ is the membership of } X_j' \text{ for the corresponding fuzzy set.}
\]

Suppose the fuzzy possibility of the basic events is $P(X_1^{i_1})(i_1 = 1, 2, \ldots, k_1), \ P(X_2^{i_2})(i_2 = 1, 2, \ldots, k_2), \ldots, P(X_n^{i_n})(in = 1, 2, \ldots, k_n)$, then the possibility of the rule $l$ is : $P_l = P(X_1^{i_1}) P(X_2^{i_2}) \ldots P(X_n^{i_n}) \ (l = 1, 2 \ldots m)$.

The fuzzy possibility of the top event is then calculated by:

\[
\begin{align*}
P(Y^1) &= \sum_{l=1}^{m} \beta_l^1 \cdot P_l(Y^1) \\
P(Y^2) &= \sum_{l=1}^{m} \beta_l^2 \cdot P_l(Y^2) \\
P(Y^k) &= \sum_{l=1}^{m} \beta_l^k \cdot P_l(Y^k)
\end{align*}
\]

(2)
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