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A FTA-based method for risk decision-making in emergency response

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ABSTRACT

Decision-making problems in emergency response are usually risky and uncertain due to the limited decision data and possible evolvement of emergency scenarios. This paper focuses on a risk decision-making problem in emergency response with several distinct characteristics including dynamic evolvement process of emergency, multiple scenarios, and impact of response actions on the emergency scenarios. A method based on Fault Tree Analysis (FTA) is proposed to solve the problem. By analyzing the evolvement process of emergency, the Fault Tree (FT) is constructed to describe the logical relations among conditions and factors resulting in the evolvement of emergency. Given different feasible response actions, the probabilities of emergency scenarios are estimated by FTA. Furthermore, the overall ranking value of each action is calculated, and a ranking of feasible response actions is determined. Finally, a case study on H1N1 infectious diseases is given to illustrate the feasibility and validity of the proposed method.

1. Introduction

Emergencies, i.e., natural disasters, industrial incidents, infectious diseases and terrorist attacks etc., often cause losses of life or injury, property damages, social and economic disruptions or environmental degradations. For example, the Severe Acute Respiratory Syndrome (SARS) broken out in east Asia early 2003 resulted in the death of hundreds of people, the global panic and the inestimable economic loss. When an emergency occurs, the relevant management personnel or decision-makers (DMs) need to decide what actions to take instantly so as to mitigate or minimize the negative effects. Usually, the decision-making problems in emergency response are complicated due to the limited decision data and possible evolvement of emergency scenarios [1,2]. Therefore, how to select an effective response action in the earlier stage of emergency is an important research topic of emergency management.

Some studies have been conducted to deal with the decision-making problem in emergency response [1–11]. For example, Hämäläinen et al. [1] proposed a multi-attribute risk analysis method to select a strategy for protecting the population in a simulated nuclear accident. Shim et al. [2] developed a decision support system (DSS) for controlling river basin flood. Körte [3] proposed a method named 'contingent risk and decision analysis' to solve the decision-making problems under variable environment. Levy [4] developed a DSS for flood risk management by integrating the multi-criteria decision-making (MCDM) method, the remote sensing, GIS, the hydrologic models, and the real-time flood information systems. Based on [4], Levy and Taji [5] proposed a group analytic network process (GANP) approach to provide a support to hazard planning and emergency management under incomplete information. Fu [6] proposed a fuzzy optimization method for selecting the most desirable action to control the flood of reservoir. Geldermann et al. [7] proposed a MCDM-based evaluation method for nuclear remediation management. Lim and Lee [8] proposed a spatial multi-criteria decision analysis approach for evaluating flood damage reduction actions. Yu and Lai [9] proposed a distance-based group decision-making (GDM) method to solve unconventional multi-person multi-criteria emergency decision-making problems. Peng et al. [10] proposed an incident information management framework based on data integration, data mining and multi-criteria decision making. Ergu et al. [11] proposed a simple consistency test process to make ANP more suitable to solve decision-making problems in emergency cases.

The existing studies have made significant contributions to decision analysis in emergency response. In existing studies, various decision-making methods are proposed according to the characteristics of different actual emergency events, such as nuclear accident [1,7], flood disaster [2,4,6,8] and so on. In some actual emergency situations, like infectious diseases and fire hazards etc., the decision-making problems have dynamic and risky characteristics. This needs to consider a special risk decision-making problem with several distinct characteristics including dynamic evolvement process of emergency, multiple scenarios, and impact of response actions on the emergency scenarios. However, the existing decision

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analysis methods seldom consider to solve the decision-making problems with the above characteristics. Therefore, it is necessary to further investigate the risk decision-making problem considering the characteristics of dynamic evolvement and multiple scenarios in emergency response.

The Fault Tree Analysis (FTA) is one of the most powerful tools for predicting reliability of a complex system by depicting the logical relations among components or sub-systems in the system. By FTA, the occurrence frequency or probability of the system hazardous events can be estimated [12–17], and the root causes of system hazardous events can be found. In this paper, we incorporate FTA into the analysis of risk decision-making problem with the characteristics of dynamic evolvement and multiple scenarios in emergency response. An emergency with multiple scenarios is regarded as a 'system', the undesirable scenarios of the emergency are regarded as 'system hazardous events', and the conditions and factors resulting in the evolvement of emergency are denoted as middle events and basic events. Accordingly, a fault tree (FT) for the emergency is constructed to describe the logical relations among scenarios, conditions and factors. Based on the constructed FT, the probabilities of emergency scenarios can be estimated with respect to each feasible response action. Furthermore, based on obtained probabilities of emergency scenarios, classical risk decision-making method can be employed to calculate the overall ranking value of each action.

The rest of this paper is organized as follows. Section 2 formulates the risk decision-making problem in emergency response based on the analysis of the practical background of SARS diseases. In Section 3, the FT for an emergency is constructed to describe the logical relations among the conditions and factors resulting in the evolvement of emergency scenarios. In Section 4, the probabilities of emergency scenarios are calculated with respect to each feasible response action. Section 5 provides an approach to ranking feasible response actions by calculating overall ranking values of actions. Section 6 demonstrates a case study on the H1N1 infectious diseases. Finally, Section 7 summarizes and highlights the main features of this paper.

2. The risk decision-making problem in emergency response

In this section, we first analyze the practical background of SARS diseases, and then describe the risk decision-making problem in emergency response.

2.1. SARS diseases

SARS is a contagious respiratory disease caused by the SARS corona virus. The first case of SARS was found in Guangdong province in China on November 16, 2002. Since there was no precedent of SARS, an inefficient control action was implemented, which leaded to a rapidly spreading of SARS. In early 2003, more infected cases were successively found in different provinces in China, including, 6 cases in Guangxi province on January 4, 3 cases in Sichuan province on February 10, and 1 case in Hunan province on February 14, etc. SARS continuously spread to other countries and regions by traveling passengers. On February 15, 2003, a doctor from Guangdong province, who had been infected by SARS, arrived at Hongkong, and infected 15 hotel visitors. The infected visitors then traveled to Canada, Singapore, Taiwan and Vietnam, and caused further widely spreading of SARS. According to the report of the World Health Organization (WHO), the SARS disease in 2003 resulted in 8096 known infected cases, 774 confirmed human deaths, the global panic and the inestimable economical loss.

Comparing with the explosive spreading of SARS in 2003, the recurrence of SARS in 2004 was rarely known by public. Two infected cases were respectively found in Beijing and Hefei in April 2004 [18]. The first infected case was a researcher working in a lab of SARS corona virus. Based on the experience obtained in 2003, an effective action was taken to control the spreading of SARS in no time. It restricted the disease to only 9 infected cases finally.

It can be seen from the above practical background of SARS diseases in 2003 and 2004 that emergency response is a risk decision-making problem. Take the spreading of SARS as an example, the emergency response problem usually has the following distinct characteristics: (1) the spreading of SARS disease is dynamic; (2) the spreading of SARS has multiple possible scenarios, and the probability of each scenario is variational; (3) each action of emergency response would change the probabilities of scenarios. Therefore, in order to find the most desirable control action, it is necessary to estimate the probabilities of scenarios by analyzing the conditions and factors that could impact the evolvement of emergency.

2.2. Problem description

Based on the above analysis of practical background of an emergency situation, SARS, we depict a new risk decision-making problem in emergency response in this paper. The following notations are used to describe the problem.

- $A=\{A_1,A_2,\ldots,A_m\}$: the set of m feasible response actions (alternatives), where A_i denotes the ith response action, $i=1,2,\ldots,m$.
- $O=(o_1,o_2,\ldots,o_m)$: the vector of costs, where o_i denotes the cost of action A_i, $i=1,2,\ldots,m$. Usually, the cost of action A_i consists of several parts, such as the cost of human resource, the cost of relief goods and so on. For the convenience of analysis, let o_i denote the total cost of A_i composed of all parts, $i=1,2,\ldots,m$, and it is in monetary form.
- $S=(S_0,S_1,\ldots,S_n)$: the scenario vector, where S_0 denotes the current scenario of the emergency; S_j denotes the jth potential scenario in the evolvement process of the emergency, $j=1,2,\cdots,n$. In this paper, we further define the damage result under scenario $S_{j'}$ is more serious than that under S_j, if $j'>j$, $\forall j,j'\in\{0,1,\ldots,n\}$. In addition, we assume that scenarios $S_0,S_1,\ldots,S_n$ are sequential, and in other words, $S_{j'}$ could occur only if S_j has already occurred, if$j'>j$. Usually, vector S can be determined by consulting experts, collecting related statistical data or conducting study on cases.
- $D=\{D_1,D_2,\ldots,D_q\}$: the set of q criteria for describing the damage result of emergency, where D_k denotes the kth criterion for describing the damage result, $k=1,2,\ldots,q$.
- $d_j=(d_{j1},d_{j2},\ldots,d_{jq})$: the damage result vector under scenario S_j, where d_{jk} is the damage result concerning criterion D_k and under scenario S_j, $j=0,1,2,\cdots,n$, $k=1,2,\ldots,q$.
- w^{cost}: the weight of cost, $0\le w^{\text{cost}}<1$.
- $W=(w_1,w_2,\ldots,w_q)$: the vector of criterion weights, where w_k is the weight of criterion D_k, $0\le w_k\le 1$, $k=1,2,\ldots,q$. Here, we consider $w^{\text{cost}}+\sum_{k=1}^{q} w_k=1$. Usually, w^{cost} and W can be obtained either directly from the assignment of the DM or indirectly using existing procedures such as AHP [19,20].
- $P=[p_{ij}]_{m\times n}$: the probability matrix, where p_{ij} denotes the probability of scenario S_j if response action A_i is taken, $i=1,2,\ldots,m$, $j=1,2,\ldots,n$. Usually, P is unknown in the earlier stage of emergency, which is needed to be estimated by an appropriate approach.

The problem mainly addressed in this paper is how to estimate P and to select the most desirable response action(s) among set A based on O, d_j, w^{cost}, W and the obtained P.

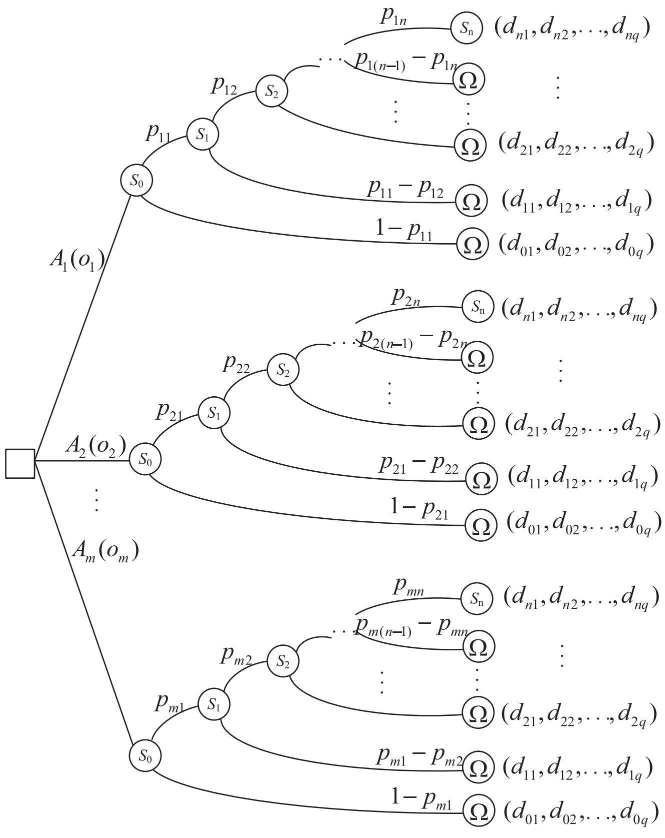

Fig. 1. The risk decision-making problem in emergency response.

As we mentioned before, the problem is a risk decision-making problem. We describe it as a decision tree in Fig. 1. It can be seen from Fig. 1 that there are two possible results of scenario S_0 if response action A_i is implemented, i.e., either the emergency will evolve into scenario S_1 with probability p_{i1} or end (Ω) with probability $1-p_{i1}$. Furthermore, if the emergency evolves into scenario S_1, there are also two possible results, i.e., either the emergency will evolve into scenario S_2 with probability p_{i2} or end (Ω) with probability $p_{i1}-p_{i2}$. Similarly, if the emergency evolves into scenario S_{n-1}, there are also two possible results, i.e., either the emergency will evolve into scenario S_n with probability p_{in} or end (Ω) with probability $p_{i(n-1)}-p_{in}$. If the emergency ends after the occurrence of scenario S_j, then damage result vector is $d_j=(d_{j1},d_{j2},...,d_{jq})$.

Remark 1. It is necessary to point out that p_{ij} is the probability of scenario S_j given that response action A_i is implemented, rather than the conditional probabilities of scenario S_j given that scenario S_{j-1} has occurred, $i=1,2,...,m$, $j=1,2,\cdots,n$.

To solve the risk decision-making problem described above, a FTA-based method is proposed. First, a FT is constructed to depict the logical relations among conditions and factors resulting in the evolvement of emergency. Then, based on the constructed FT, the probabilities of different scenarios are calculated given different response actions. Furthermore, based on the obtained probabilities, the overall ranking value of each action is calculated to determine a ranking of the feasible response actions. In the next section, we will construct the FT for an emergency.

3. Constructing the FT for an emergency

FTA is a powerful diagnosis technique and widely used for demonstrating the root causes of undesirable event in system failure, as well as depicting the logical relations among components, manufacturing processes, and sub-systems [12–17]. It was originally developed by Bell Laboratories for the US Air Force in 1962 and was later adopted and extensively applied by the Boeing Company. Now, FTA is wildly used in many fields, such as chemical industries [16], liquefied natural gas terminal emergency shutdown system [17] and so on. In this paper, the principle of FTA is employed to estimate the probabilities of emergency scenarios. Thus, constructing a FT beforehand is necessary in order to depict the logical relations among the conditions and factors driving the evolvement of emergency scenarios. In the following, we first introduce the basic components of FT, and then give the steps for constructing the FT for an emergency.

3.1. Basic components of FT

Usually, a FT is composed of a series of events and logic gates. The main events include:

- *Top event*: is the most undesirable system failure event and the object of the analysis, denoted as □.
- *Middle event*: is the sub-system or component failure event and the cause of the top event, denoted as □.
- *Basic event*: is the primary failure event and the cause of the top event or middle events, denoted as ○.
- The main logic gates include:
- *Logic gate 'OR'*: indicates that output event occurs if at least one of the input events occurs, denoted as △.
- *Logic gate 'AND'*: indicates that output event occurs only if all of the input events occur, denoted as ∩.

There may be many other types of events and logic gates involved in complex system reliability analysis, but, for the sake of concisions, we only list the most commonly used ones here. For other types of events and logic gates, please refer to [14–15].

3.2. Steps for constructing the FT for an emergency

The construction of the FT for an emergency is a deductive procedure. The core idea is to identify the conditions and factors that emergency can evolve into scenario S_j from scenario S_{j-1}, $j=1,2,...,n$. The FT should be developed level by level, and each level should be completed before any consideration is given to the next level. To successfully construct the FT for an emergency, the following steps are suggested:

Step 1. The most undesirable scenario S_n is defined as top event.
Step 2. Define boundary conditions for the analysis. The boundary conditions include: (1) physical boundaries: define what factors, status and emergency scenarios will be included in the FT as events; (2) boundary conditions concerning environmental stresses: define what external stresses (e.g., virus variation) should be included in the FT as events; (3) level of resolution: determine how far down we should identify the potential reasons for an event in detail.
Step 3. Classify all events into middle events and basic events. If an event represents a primary factor that may result in the evolvement of emergency, it is classified as a basic event; if an event represents a secondary factor that may result in the evolvement of emergency, it is classified as a middle event that requires a further investigation to identify the prime causes.
Step 4. Complete the gates. If the upper level event will occur given that a single lower event occurs, then the events should be linked with 'OR' gate; if the upper level event will occur

only if two or more lower events occur simultaneously, then the events should be linked with 'AND' gate.

Using the above steps, the FT for an emergency can be constructed. In addition, computer-aided FT construction methods have also been proposed in literatures [21–25], which can also be used to construct the FT for an emergency.

4. Calculating the probabilities of scenarios

Based on the constructed FT, a logical expression of each scenario can be formulated. Then, by estimating the probabilities of basic events, the probabilities of scenarios can be calculated given different response actions. In the following, the procedure for calculating the probabilities is briefly described.

Suppose there are l basic events in the FT for an emergency, denoted as $X_1, X_2, \ldots, X_l$, respectively. According to the constructed FT, a logical expression of scenario S_j is first formulated as

$$F_{S_j} = F_j(X_1, X_2, \ldots, X_l),\ j = 1,2,\ldots,n \tag{1}$$

In the logical expression, the basic events or middle events are linked by logic operation symbol '$\oplus$' if they are linked by 'OR' gate (⋀) in the constructed FT; the basic events or middle events are linked by logic operation symbol '$\otimes$' if they are linked by 'AND' gate (⋂) in the constructed FT.

Next, in order to estimate the probabilities of basic events, several experts should be invited to participate in the decision analysis. In fact, it is not easy for the experts to determine or define the probabilities of basic events directly since many factors need to be considered. In this situation, the indirect elicitation technique [26,27], Delphi method [28] or Nominal Group Technique [29] can be used to determine the probabilities of basic events. In the indirect elicitation technique, a series of data on historical similar events are provided to the experts. Then, the experts are asked to compare the probabilities of basic events with those of historical similar events, which will be helpful to determine the experts' personal judgment on the probabilities of basic events. Further, based on the experts' personal judgment, Delphi method [28] and Nominal Group Technique [29] are employed to determine a consistency collective judgment on the probabilities of basic events. Therefore, a probability matrix of basic events can be obtained, which is represented by

$$\Theta = [\rho_{ih}]_{m\times l} = \begin{array}{c|cccc|} & X_1 & X_2 & \cdots & X_l \\ A_1 & \rho_{11} & \rho_{12} & \cdots & \rho_{1l} \\ A_2 & \rho_{21} & \rho_{22} & \cdots & \rho_{2l} \\ \vdots & \vdots & \vdots & & \vdots \\ A_m & \rho_{m1} & \rho_{m2} & \cdots & \rho_{ml} \end{array}$$

In $\Theta = [\rho_{ih}]_{m\times l}$, ρ_{ih} denotes the probability of basic event X_h if response action A_i is implemented, $i = 1,2,\ldots,m$, $h = 1,2,\ldots,l$.

Furthermore, according to F_{S_j} and $\Theta = [\rho_{ih}]_{m\times l}$, the probability of scenario S_j given response action A_i can be calculated by

$$p_{ij} = f_j(\rho_{i1}, \rho_{i2}, \ldots, \rho_{il}), \quad i = 1,2,\ldots,m, \quad j = 1,2,\ldots,n \tag{2}$$

where $f_j(\cdot)$ is the function corresponding to $F_j(\cdot)$. In $f_j(\cdot)$, the logic operation $X_h \oplus X_{h'}$ in $F_j(\cdot)$ is replaced by probability operation $\rho_{ih} + \rho_{ih'} - \rho_{ih}\rho_{ih'}$; the logic operation $X_h \otimes X_{h'}$ in $F_j(\cdot)$ is replaced by $\rho_{ih}\rho_{ih'}$. Therefore, according to p_{ij}, $i = 1,2,\ldots,m$, $j = 1,2,\ldots,n$, the probability matrix of scenarios is constructed, i.e.,

$$P = [p_{ij}]_{m\times n} = \begin{array}{c|cccc|} & S_1 & S_2 & \cdots & S_n \\ A_1 & p_{11} & p_{12} & \cdots & p_{1n} \\ A_2 & p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & & \vdots \\ A_m & p_{m1} & p_{m2} & \cdots & p_{mn} \end{array}$$

where p_{ij} denotes the probability of scenario S_j if action A_i is implemented, $i = 1,2,\ldots,m$, $j = 1,2,\ldots,n$.

To illustrate the above computation procedure more clearly, a simple numerical example is given below.

Example 1. Fig. 2 shows an illustrative example of the FT for an emergency.

In Fig. 2, S_2 is the most undesirable scenario of emergency (top event); S_1 is an undesirable scenario in the lower level of S_2, and M_1 is the middle events; X_1, X_2, X_3 and X_4 are four basic events. X_1, X_2 and S_1 are linked by ⋀. It denotes that S_1 occurs if at least one of X_1 and X_2 occurs. X_3, X_4 and M_1 are linked by ⋂. It denotes that M_1 occurs only if all of X_3 and X_4 occur simultaneously. Similarly, S_2 occurs only if all of S_1 and M_1occur simultaneously.

According to Fig. 2, the logical expressions of S_1 and S_2 can be respectively formulated, i.e.,

$$F_{S_1} = X_1 \oplus X_2, \tag{3}$$

$$F_{S_2} = S_1 \otimes M_1 = (X_1 \oplus X_2) \otimes (X_3 \otimes X_4), \tag{4}$$

where $\oplus$ and $\otimes$ denote the logic operations of 'OR' and 'AND'.

Suppose two feasible response actions (or alternatives) A_1 and A_2 are considered to be implemented in emergency response.

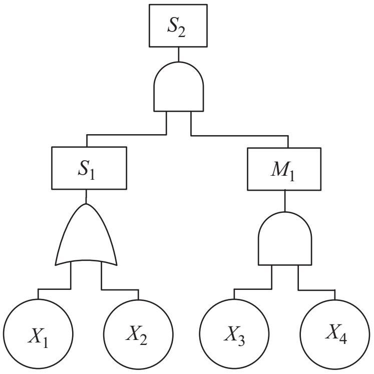

Fig. 2. An illustrative example of FT.

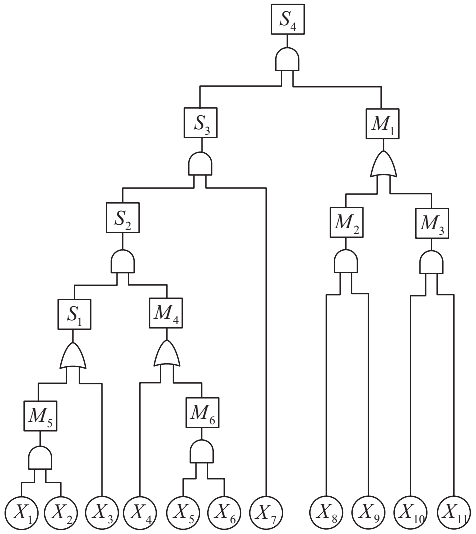

Fig. 3. The FT for H1N1 infectious disease in University B.

The probability matrix of basic events determined by indirect elicitation technique and Delphi method is

$$\Theta=[\rho_{ih}]_{2\times 4}=\begin{array}{c|cccc} & X_1 & X_2 & X_3 & X_4 \\ \hline A_1 & 0.8 & 0.6 & 0.4 & 0.2 \\ A_2 & 0.7 & 0.7 & 0.3 & 0.4 \end{array}$$

Then, according to Eq. (3) and matrix Θ, the probability of S_1 can be calculated given action A_1 or A_2, i.e.,

$$p_{11}=0.8+0.6-0.8\times 0.6=0.92, \tag{5}$$

$$p_{21}=0.7+0.7-0.7\times 0.7=0.91, \tag{6}$$

Similarly, according to Eq. (4) and matrix Θ, the probability of S_2 can be calculated given action A_1 or A_2, i.e.,

$$p_{12}=(0.8+0.6-0.8\times 0.6)\times 0.4\times 0.2=0.0736, \tag{7}$$

$$p_{22}=(0.7+0.7-0.7\times 0.7)\times 0.3\times 0.4=0.1092, \tag{8}$$

Therefore, we can construct the probability matrix of scenarios, i.e.,

$$P=[p_{ij}]_{2\times 2}=\begin{array}{c|cc} & S_1 & S_2 \\ \hline A_1 & 0.92 & 0.0736 \\ A_2 & 0.91 & 0.1092 \end{array}$$

5. Determining the ranking of feasible response actions

Based on $P=[p_{ij}]_{m\times n}$, the overall ranking values of different response actions can be calculated to determine a ranking of actions. In the following, we briefly described the computation procedure of overall ranking values.

First, to make different criteria have the same range of measurement, the costs and criterion values are normalized into the numbers from 0 to 1 respectively. Let $\overline{O}=(\overline{o}_1,\overline{o}_2,\ldots,\overline{o}_m)$ be the vector of normalized costs, where $\overline{o}_i$ is the normalized cost of response action A_i, $i=1,2,\ldots,m$. Let $\overline{d}_j=(\overline{d}_{j1},\overline{d}_{j2},\ldots,\overline{d}_{jq})$ be the vector of normalized criterion values, where $\overline{d}_{jk}$ is the normalized criterion value concerning D_k with respect to scenario S_j, $j=0,1,2,\ldots,n$, $k=1,2,\ldots,q$. The calculation formulas of $\overline{o}_i$ and $\overline{d}_{jk}$ can be respectively expressed by

$$\overline{o}_i=\frac{o^{\max}-o_i}{o^{\max}-o^{\min}},\quad i=1,2,\ldots,m \tag{9}$$

$$\overline{d}_{jk}=\frac{d_k^{\max}-d_{jk}}{d_k^{\max}-d_k^{\min}},\quad j=0,1,2,\ldots,n,\quad k=1,2,\ldots,q \tag{10}$$

where $o^{\max}=\max\{o_1,o_2,\ldots,o_m\}$ and $o^{\min}=\min\{o_1,o_2,\ldots,o_m\}$; $d_k^{\max}=\max\{d_{0k},d_{1k},d_{2k},\ldots,d_{nk}\}$ and $d_k^{\min}=\min\{d_{0k},d_{1k},d_{2k},\ldots,d_{nk}\}$. By Eqs. (9) and (10), the costs and criterion values are all unified into benefit type [30,31], i.e., the greater $\overline{o}_i$ is, the better action A_i will be; similarly, the greater $\overline{d}_{jk}$ is, the better damage result concerning D_k with respect to scenario S_j will be.

It can be seen from Fig. 1 that there are $n+1$ possible damage results, i.e., the emergency ends after the occurrence of scenario S_0, S_1, S_2, …, or S_n. The probabilities of the $n+1$ damage results are $1-p_{i1}$, $p_{i1}-p_{i2}$, $p_{i2}-p_{i3}$,… and p_{in} if response action A_i is implemented. Let a_{ik} denote the expected criterion value of action A_i concerning D_k, $i=1,2,\ldots,m$, $k=1,2,\ldots,q$. According to $\overline{d}_j=(\overline{d}_{j1},\overline{d}_{j2},\ldots,\overline{d}_{jq})$ and $P=[p_{ij}]_{m\times n}$, a_{ik} can be represented by

$$a_{ik}=(1-p_{i1})\overline{d}_{01}+\sum_{j=1}^{n-1}(p_{ij}-p_{i(j+1)})\overline{d}_{jk}+p_{in}\overline{d}_{nk},\quad i=1,2,\ldots,m,\quad k=1,2,\ldots,q \tag{11}$$

Furthermore, let a_i denote the overall ranking value of response action A_i, which can be represented by

$$a_i=w^{\text{cost}}\overline{o}_i+\sum_{k=1}^{q}w_k a_{ik},\quad i=1,2,\ldots,m \tag{12}$$

In Eq. (12), w^{cost} is the weight of cost, w_k is the weight of criterion D_k, $k=1,2,\ldots,q$.

It can be seen that the greater a_i is, the better response action A_i will be. Therefore, according to overall ranking values $a_1,a_2,\ldots,a_m$, we can determine a ranking of all feasible response actions.

In summary, the steps of the FTA-based method for risk decision-making in emergency response are given below.

Step 1. Construct the FT for an emergency using the steps proposed in Section 3.2.
Step 2. Determine logical expression F_{S_j} according to Eq. (1), $j=1,2,\ldots,n$.
Step 3. Determine matrix $\Theta=[\rho_{ih}]_{m\times l}$ using indirect elicitation technique and Delphi method.
Step 4. Calculate p_{ij} using Eq. (2), $i=1,2,\ldots,m$, $j=1,2,\ldots,n$.
Step 5. Determine $\overline{O}=(\overline{o}_1,\overline{o}_2,\ldots,\overline{o}_m)$ and $\overline{d}_j=(\overline{d}_{j1},\overline{d}_{j2},\ldots,\overline{d}_{jq})$ using Eqs. (9) and (10), $j=1,2,\ldots,n$.
Step 6. Calculate a_{ik} using Eq. (11), $i=1,2,\ldots,m$, $k=1,2,\ldots,q$.
Step 7. Calculate a_i using Eq. (12), $i=1,2,\ldots,m$.
Step 8. Determine a ranking of all feasible response actions according to $a_1,a_2,\ldots,a_m$.

6. Case study

In this section, to illustrate the feasibility and validity of the FTA-based method, we investigate a case on H1N1 infectious disease in University B, one of the most famous universities in China. First, the introduction of the case is given. Then, the FTA-based method is used to choose a desirable response action for controlling the spreading of H1N1 in the university. In addition, a sensitivity analysis is conducted to show the impact of parameters on the ranking of feasible response actions.

6.1. *Introduction of the case*

H1N1 virus is a subtype of influenza A virus and was the most common cause of human influenza in 2009. In September, an infected person of H1N1 was diagnosed in University B, which has 30,000 students and staff living on campus. After persuading the infected person to take quarantine measures, the university needs to take further action to control the spreading of H1N1 by selecting one from six feasible emergency response actions. The six feasible response actions are given as below.

- A_1: Taking no additional countermeasures. The cost of A_1 is 0 million RMB, $o_1=0$;
- • A_2: Persuading all close contacts of the infected person to take quarantine measures. The cost of A_2 is 0.1 million RMB, $o_2=0.1$;
- A_3: Adopting A_2 and furthermore, providing antisepsis equipments to dormitories and classrooms of the infected person, and measuring the temperatures of relevant students and staff every 12 h. The cost of A_3 is 0.2 million RMB, $o_3=0.2$;
- A_4: Adopting A_3 and furthermore, suspending the classes in the institute of the infected person, and control the flow of people between the institute and other institutes. The cost of A_4 is 0.5 million RMB, $o_4=0.5$;
- A_5: Adopting A_4 and furthermore, providing antisepsis equipments to all dormitories and classrooms, and measuring the

temperatures of all students and staff of the university every 12 h. The cost of A_5 is 0.8 million RMB, $o_5 = 0.8$;
- A_6: Adopting A_5 and furthermore, suspending all classes in the university. The cost of A_6 is 2 million RMB, $o_6 = 2$.

To select a desirable response action, the university invited five experts of epidemiology and three experts of emergency management to participate in the decision-making process. By consulting the experts, four potential scenarios in the evolvement process of infectious disease are determined as below.

- S_1: New infected persons are detected in the infected person's close contacts.
- S_2: New infected persons are detected in the same institute or dormitories of the infected person and his/her close contacts.
- S_3: Multiple new infected persons are detected in other institutes and dormitories.
- S_4: The pandemic of H1N1 in University B.

When make a decision, the following criteria are considered:

- D_1: the number of infected persons;
- D_2: the panic degree of students and staff;
- D_3: the negative effect on the reputation of the university.

The DM provides the weight of cost and weight vector of criteria, i.e., $w^{cost} = 0.1$ and $W = (0.6,\ 0.2,\ 0.1)$. The values concerning criterion D_1 are estimated by experts; the values concerning D_2 and D_3 are evaluated by experts in the scale of scores of 0–100 (0: no panic or negative effect; 100: serious panic or negative effect). The criterion values with respect to different scenarios are shown in Table 1.

Table 1
The criterion values with respect to different scenarios.

d_{jk}	D_1	D_2	D_3
S_0	0	0	0
S_1	10	20	10
S_2	40	50	40
S_3	100	80	70
S_4	200	100	100

6.2. Choosing a desirable response action using the FTA-based method

To select a desirable action, the FTA-based method proposed in this paper is used and the procedure is summarized as follows.

6.2.1. Constructing the FT for H1N1 infectious disease in the university

The most undesirable scenario S_4 is defined as the top event. Then, according to the analysis of historical similar infectious diseases, the conditions or factors that could result in scenario S_4 are identified, i.e., "Multiple new infected persons are detected in other institutes and dormitories (S_3)" and "The infection routes are unclear (M_1)". Additionally, S_4, S_3 and M_1 are linked by 'AND' gate (⋂) since S_4 will occur only if S_3 and M_1 occur simultaneously.

Similarly, the causes of S_3 are identified, i.e., "New infected persons are detected in the same institute or dormitories of the infected person and his/her close contacts (S_2)" and "New infected persons have contacted persons in other institutes and dormitories (X_7)". Additionally, S_3, S_2 and X_7 are also linked by 'AND' gate (⋂). The causes of M_1 are regarded as "Healthy persons are infected by intermediary, such as tableware, classroom, etc (M_2)" or "Healthy persons are infected by undetected infected ones (M_3)". M_1, M_2 and M_3 are linked by 'OR' gate (⋀) since M_1 will occur if one of M_2 and M_3 occurs.

The above deductive procedure are repeated until the root causes of scenario S_4 are analyzed clearly. Thereby, the FT for H1N1 infectious disease in University B is constructed, which is shown in Fig. 3. The meanings of the symbols in Fig. 3 are given in Table 2.

6.2.2. Calculating the probabilities of scenarios

According to Fig. 3, the logical expressions of S_1, S_2, S_3 and S_4 can be respectively formulated, i.e.,

$$F_{S_1} = (X_1 \otimes X_2) \oplus X_3, \tag{13}$$

Table 2
The meanings of symbols in Fig. 3.

Symbols	***Meanings of symbols***
S_1	New infected persons are detected in the infected person's close contacts
S_2	New infected persons are detected in the same institute or dormitories of the infected person and his/her close contacts
S_3	Multiple new infected persons are detected in other institutes and dormitories
S_4	The pandemic of H1N1 in University B
M_1	The infection routes are unclear
M_2	Healthy persons are infected by intermediary, such as tableware, classroom, etc
M_3	Healthy persons are infected by undetected infected ones
M_4	The ineffective monitoring measures on infection routes
M_5	Healthy persons are infected by the close contacts
M_6	New infected ones infect healthy persons in the same institute
X_1	The close contacts are not taken quarantine measures
X_2	The close contacts have been infected
X_3	Several persons in the same dormitory have been infected
X_4	The classrooms in the institute of the infected ones have not been disinfected timely
X_5	The infected ones in the institute are not detected timely
X_6	The infected ones contact with others in group activities of the institute
X_7	New infected persons have contacted with persons in other institutes and dormitories
X_8	The classrooms in other institutes have not been disinfected timely
X_9	The infected ones enter the classroom in other institutes
X_{10}	The infected ones in other institutes are not detected timely
X_{11}	The infected ones contact with others in group activities of the university

$$F_{S_2}=F_{S_1}\otimes(X_4\oplus(X_5\otimes X_6))=((X_1\otimes X_2)\oplus X_3)\otimes(X_4\oplus(X_5\otimes X_6)),\tag{14}$$

$$F_{S_3}=F_{S_2}\otimes X_7=((X_1\otimes X_2)\oplus X_3)\otimes(X_4\oplus(X_5\otimes X_6))\otimes X_7,\tag{15}$$

$$\begin{aligned}F_{S_4}&=F_{S_3}\otimes((X_8\otimes X_9)\oplus(X_{10}\otimes X_{11}))\\&=((X_1\otimes X_2)\oplus X_3)\otimes(X_4\oplus(X_5\otimes X_6))\\&\quad\otimes X_7\otimes((X_8\otimes X_9)\oplus(X_{10}\otimes X_{11})).\end{aligned}\tag{16}$$

Then, indirect elicitation technique [26,27] and Delphi method [28] are used to help the experts determine a consistency collective judgment on probabilities of basic events. The probability matrix of basic events is shown in Table 3.

Furthermore, according to Eqs. (2) and (13)–(16), the formulas for calculating probabilities of scenarios S_1, S_2, S_3 and S_4 are constructed with respect to action A_i, i.e.,

$$p_{i1}=\rho_{i1}\rho_{i2}+\rho_{i3}-\rho_{i1}\rho_{i2}\rho_{i3},\tag{17}$$

$$\begin{aligned}p_{i2}&=p_{i1}(\rho_{i4}+\rho_{i5}\rho_{i6}-\rho_{i4}\rho_{i5}\rho_{i6})\\&=(\rho_{i1}\rho_{i2}+\rho_{i3}-\rho_{i1}\rho_{i2}\rho_{i3})(\rho_{i4}+\rho_{i5}\rho_{i6}-\rho_{i4}\rho_{i5}\rho_{i6}),\end{aligned}\tag{18}$$

$$p_{i3}=p_{i2}\rho_{i7}=(\rho_{i1}\rho_{i2}+\rho_{i3}-\rho_{i1}\rho_{i2}\rho_{i3})(\rho_{i4}+\rho_{i5}\rho_{i6}-\rho_{i4}\rho_{i5}\rho_{i6})\rho_{i7},\tag{19}$$

$$\begin{aligned}p_{i4}&=p_{i3}(\rho_{i8}\rho_{i9}+\rho_{i10}\rho_{i11}-\rho_{i8}\rho_{i9}\rho_{i10}\rho_{i11})\\&=(\rho_{i1}\rho_{i2}+\rho_{i3}-\rho_{i1}\rho_{i2}\rho_{i3})(\rho_{i4}+\rho_{i5}\rho_{i6}\\&\quad-\rho_{i4}\rho_{i5}\rho_{i6})\rho_{i7}(\rho_{i8}\rho_{i9}+\rho_{i10}\rho_{i11}-\rho_{i8}\rho_{i9}\rho_{i10}\rho_{i11})\end{aligned}\tag{20}$$

According to Table 3 and Eqs. (17)–(20), the probabilities of scenarios given different response actions can be obtained, and shown in Table 4.

Table 3
The probability matrix of basic events.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
A_1	1	0.8	0.6	0.8	0.9	0.8	0.7	0.8	0.9	0.9	0.8
A_2	0	0.8	0.6	0.8	0.9	0.8	0.7	0.8	0.9	0.9	0.8
A_3	0	0.8	0.6	0.4	0.4	0.7	0.6	0.8	0.9	0.9	0.8
A_4	0	0.8	0.6	0.4	0.4	0.2	0.1	0.8	0.2	0.9	0.8
A_5	0	0.8	0.6	0.4	0.4	0.2	0.1	0.4	0.2	0.4	0.8
A_6	0	0.8	0.6	0.4	0.4	0.2	0.1	0.4	0.2	0.4	0.1

Table 4
The probabilities of scenarios given different response actions.

p_{ij}	S_1	S_2	S_3	S_4
A_1	0.92	0.8685	0.6079	0.5603
A_2	0.6	0.5664	0.3965	0. 3654
A_3	0.6	0.3408	0.2045	0.1884
A_4	0.6	0.2688	0.0269	0.0206
A_5	0.6	0.2688	0.0269	0.0101
A_6	0.6	0.2688	0.0269	0.0031

Table 5
The normalized criterion values.

$\overline{d}_{jk}$	D_1	D_2	D_3
S_0	1	1	1
S_1	0.95	0.8	0.9
S_2	0.8	0.5	0.6
S_3	0.5	0.2	0.3
S_4	0	0	0

Table 6
The expected criterion values of different actions.

a_{ik}	D_1	D_2	D_3
A_1	0.3612	0.2610	0.2970
A_2	0.5834	0.5181	0.5415
A_3	0.7633	0.6787	0.7199
A_4	0.9113	0.7872	0.8451
A_5	0.9166	0.7893	0.8483
A_6	0.9200	0.7907	0.8504

6.2.3. *Determining the ranking of actions*

Using Eq. (9), the vector of normalized costs is determined, i.e., $\overline{O}=(1,0.95,0.9,0.75,0.6,0)$; using Eq. (10), the normalized criterion values are obtained, and shown in Table 5. Then, using Eq. (11), the expected criterion values of different actions are determined, and shown in Table 6. Using Eq. (12), the overall ranking value of each action is determined, i.e.,

$a_1=0.3986$, $a_2=0.6028$, $a_3=0.7557$, $a_4=0.8638$, $a_5=0.8526$, $a_6=0.7952$.

Finally, according to the overall ranking values, a ranking of all feasible response actions is determined, i.e., $A_4\succ A_5\succ A_6\succ A_3\succ A_2\succ A_1$.

6.3. *Sensitivity analysis*

In the following, a sensitivity analysis is conducted to show the impact of parameters on the ranking of feasible response actions. The sensitivity analysis includes two parts. One is to analyze the impact of the weight of cost on ranking of actions. The other is to analyze the impact of probabilities of basic events on ranking of actions.

6.3.1. *The impact of the weight of cost on ranking of actions*

The weight of cost implies the relative importance degree of cost comparing with the damage results. Analyzing the influence of weight of cost on ranking of actions would provide more valuable data for decision analysis in emergency response.

Consider the weight of cost is changed to $w^{\text{cost}'}$, $0\le w^{\text{cost}'}<1$. It can be seen that $w^{\text{cost}'}+\sum_{k=1}^{q} w_k\ne 1$ if $w^{\text{cost}'}\ne w^{\text{cost}}$. Let $W'=(w'_1,w'_2,\ldots,w'_q)$ be the vector of criterion weights corresponding to $w^{\text{cost}'}$. Then, we have

$$w'_k=\frac{w_k(1-w^{\text{cost}'})}{1-w^{\text{cost}}},\quad k=1,2,\ldots,q\tag{21}$$

obviously, $w^{\text{cost}'}+\sum_{k=1}^{q} w_k{}'=1$.

In the above case study, we have $w^{\text{cost}}=0.1$ and $W=(0.6,\ 0.2,\ 0.1)$. If $w^{\text{cost}}=0.1$ is changed into $w^{\text{cost}'}=0.01$, then according to Eq. (21), we have $W'=(0.66,0.22,0.11)$. Furthermore, according to Eq. (12), the overall ranking value of each response action can be determined, i.e., $a_1=0.3385$, $a_2=0.5681$, $a_3=0.7413$, $a_4=0.8751$, $a_5=0.8779$, $a_6=0.8747$. Thus, a new ranking result of feasible response actions can be obtained, i.e., $A_5\succ A_4\succ A_6\succ A_3\succ A_2\succ A_1$.

The overall ranking values of the six feasible response actions with regard to different $w^{\text{cost}'}$ are plotted in Fig. 4. It can be seen from Fig. 4 that action A_1, A_2 or A_3 should be selected if $w^{\text{cost}'}$ is greater. Conversely, action A_4, A_5 or A_6 should be selected if $w^{\text{cost}'}$ is smaller.

6.3.2. *The impact of probabilities of basic events on ranking of actions*

There are two types of basic events in the FT for an emergency case. The first type includes the events used to describe the current scenario of emergency, whose probabilities will not change with different response actions, such as X_2 and X_3 in Fig. 3. The second

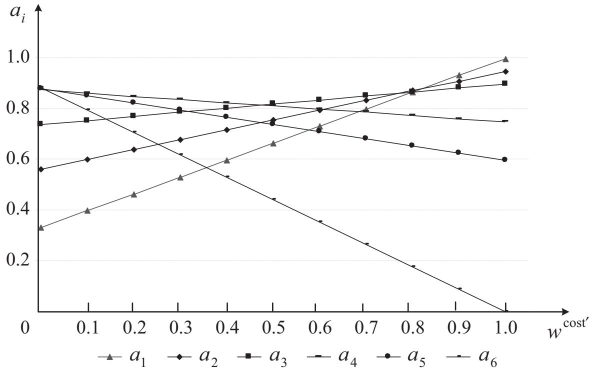

Fig. 4. Curves of overall ranking values of the six feasible response actions with regard to different $w^{\text{cost}'}$.

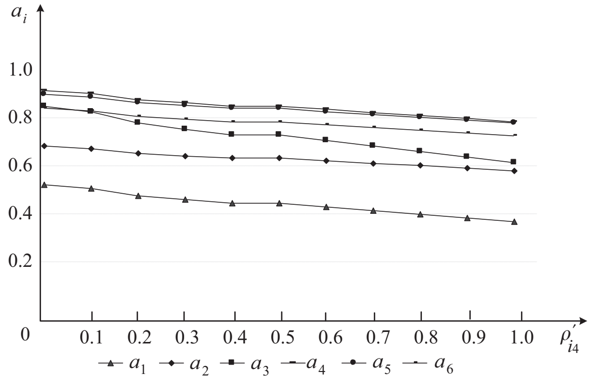

Fig. 6. Curves of overall ranking values of the six feasible response actions with regard to different ρ'_{i4}.

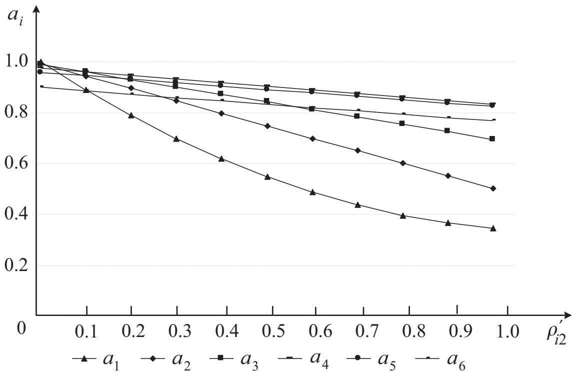

Fig. 5. Curves of overall ranking values of the six feasible response actions with regard to different ρ'_{i2}.

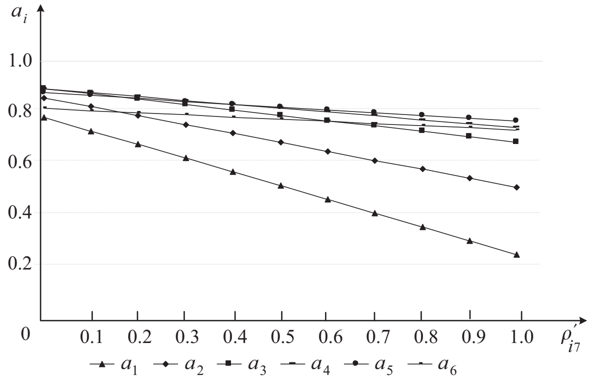

Fig. 7. Curves of overall ranking values of the six feasible response actions with regard to different ρ'_{i7}.

type includes the events used to describe conditions and factors resulting in the evolvement of emergency, whose probabilities will change with different response actions, such as X_1, X_4,X_5,…,X_{11}. In the following, the sensitivity analysis will be respectively conducted with respect to the probabilities of each type of events.

It can be seen from Fig. 3, Tables 2 and 3 that X_2 and X_3 belong to the first type of basic events. If the first infected person has not been detected timely, then the probabilities of X_2 and X_3 would be greater. Conversely, probabilities of X_2 and X_3 would be smaller. In addition, it can be seen from the practical meanings of X_2 and X_3 that there is inter-dependence between the probabilities of X_2 and X_3. In other words, if the probability of X_2 is greater, then the probability of X_3 is also greater. Consider the probabilities of X_2 and X_3 are changed to ρ'_{i2} and ρ'_{i3}, respectively. Here, for the convince of analysis, we suppose $\rho'_{i3}=0.75\rho'_{i2}$. The overall ranking values of the six feasible response actions with regard to different values of ρ'_{i2} are plotted in Fig. 5.

It can be seen from Fig. 5 that all of the overall ranking values of actions decrease with the increase of ρ'_{i2}. Action A_1 is the best one only if ρ'_{i2} approaches 0.

It can be seen from Fig. 3, Tables 2 and 3 that X_1, X_4,X_5,…,X_{11} belong to the second type of basic events. Here, we take X_4 and X_7 as two examples. Consider the probabilities of X_4 and X_7 are respectively changed to ρ'_{i4} and ρ'_{i7}. The overall ranking values of the six feasible response actions with regard to different ρ'_{i4} and ρ'_{i7} are plotted in Figs. 6 and 7, respectively.

Figs. 6 and 7 show that the overall ranking values are more sensitive to ρ'_{i7} than ρ'_{i4}. Thus, preventing the occurrence of X_7 will more effectively mitigate/reduce the expected damage results of emergency.

7. Conclusions

This paper presents a novel FTA-based method for risk decision-making in emergency response. By constructing the FT, the logical relations among the conditions and factors driving the evolvement of emergency are described. Then, based on the constructed FT, the probabilities of emergency scenarios are estimated given each feasible action. Furthermore, according to the obtained probabilities, the ranking of actions is determined by calculating the overall ranking values of feasible actions. The major contributions of this paper are discussed as follows.

First, this paper discovers and formulates a new risk decision-making problem in emergency response with distinct characteristics including the dynamic evolvement of emergency, multiple scenarios and their probabilities, and influence of response actions on probabilities of the scenarios. It is a new idea for describing the decision-making problem in emergency response and lays a good foundation for further conducting studies on risk decision analysis in emergency response.

Second, the key of the proposed method is to estimate the probabilities of scenarios given each feasible response action. For this, the principle of FTA is introduced, and the steps for constructing the FT for an emergency are given. The attempt to introduce FTA into decision analysis makes it possible to capture the dynamic evolvement process of emergency and estimate the probabilities of emergency scenarios before the response actions are implemented. It is valuable and important for developing and enriching theories and methods of decision analysis in emergency response.

Third, using the proposed method, not only the ranking of feasible response actions can be derived, but also the sensitivity analysis can be conducted conveniently. The data obtained by sensitivity analysis provide supplement and inducement to DMs, which is important to support the decision-making of DMs in the process of emergency response.

It is important to highlight that, since the proposed method is new and different from the existing methods, it can give experts or decision analysts one more choice for identifying the appropriate method to solve the problem of emergency response.

In terms of future research, two directions are worthy of pursuing. One is to extend the proposed method to the situation that probabilities or possibility of basic events are in the form of uncertain or fuzzy data, such as interval numbers, linguistic terms or institution fuzzy numbers. The other is to develop the dynamic risk decision-making methods in emergency response on the basis of the method proposed in this paper.

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