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Risk decision analysis in emergency response: A method based on cumulative prospect theory

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ABSTRACT

Emergency response of a disaster is generally a risk decision-making problem with multiple states. In emergency response analysis, it is necessary to consider decision-maker's (DM's) psychological behavior such as reference dependence, loss aversion and judgmental distortion, whereas DM's behavior is neglected in the existing studies on emergency response. In this paper, a risk decision analysis method based on cumulative prospect theory (CPT) is proposed to solve the risk decision-making problem in emergency response. The formulation and solution procedure of the studied emergency response problem are given. Then, according to CPT, the values of potential response results concerning each criterion are calculated. Consider the interdependence or conflict among criteria, Choquet integral is used to determine the values of each potential response result. Accordingly, the weights of probabilities of all potential response results are calculated. Furthermore, by aggregating the values and weights of response results, the prospect value of each response action (alternative) is determined, and overall prospect value of each response action is obtained by aggregating the prospect value and the cost of each action. According to the obtained overall prospect values, a ranking of all response actions can be determined. Finally, based on the background of emergency evacuation from barrier lake downstream villages, an example is given to illustrate the feasibility and validity of the proposed method.

1. Introduction

In recent years, various emergency events have caused huge loss of lives and property, such as the "9.11" terrorist attacks in USA, the Wenchuan earthquake in China and so on. When an emergency event occurs, the emergency management personnel or decision-makers (DMs) always need to make a reasonable emergency response or select a desirable response action to reduce the consequent negative effect. Generally, decision-making problems in emergency response are complicated due to evolutions of disaster scenario and uncertainty of decision information [1,2]. Therefore, the study on decision-making method in emergency response is an important topic.

Some decision analysis methods have been proposed to solve emergency response problems [1,3–8]. For example, Hämäläinen et al. [1] proposed a method based on multiple attributes utility theory (MAUT) to select a desirable response action for protecting the population in a nuclear accident. Körte [3] suggested a risk analysis method to deal with the emergency decision-making problem under variable environment. Levy and Taji [4] developed a method based on group analytic network process (GANP) to support hazard planning and emergency management under incomplete information. Fu [5] proposed a fuzzy optimization method to select the most desirable action for controlling the flood of reservoir. Geldermann et al. [6] suggested a MCDM-based evaluation method to select the best one among multiple feasible nuclear remediation actions. Lim and Lee [7] developed a multi-criteria decision analysis method to evaluate the actions for reducing flood damage. Yu and Lai [8] proposed a distance-based group decision-making (GDM) method to solve unconventional multi-person multi-criteria emergency decision-making problems. Ergu et al. [9] proposed a simple consistency test process to make ANP more suitable to solve decision-making problems in emergency cases. Besides, some studies on decision support systems and information systems for emergency response can be found [2,10,11]. Shim et al. [2] developed a decision support system for controlling the flood in a river basin. Levy [10] developed a decision support system for flood risk management, which incorporated MCDM method, remote sensing, GIS, hydrologic models and real-time flood information systems. Peng et al. [11] proposed an incident information management framework by integrating data integration, data mining and MCDM method.

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The existing studies have made significant contributions to decision analysis in emergency response. These studies provided various decision analysis methods for emergency response to support the DMs' decision-making. However, in the existing decision analysis methods for emergency response, the DM's behavior is rarely considered. A lot of psychological studies have shown that there are several psychological characteristics of human behavior under risk and uncertainty, such as reference dependence, loss aversion, and judgmental distortion of likelihood of almost impossible and certain outcomes [12–18]. Since decision-making problems in emergency response are usually risky and uncertain, it is necessary to consider the DM's psychological behavior in decision analysis. Therefore, it is urgent to investigate the risk decision analysis methods considering human behavior for the purpose of providing effective decision support to the DM in emergency response.

Since Tversky and Kahneman [13] proposed prospect theory [12], some behavioral decision-making theories have been developed rapidly. For example, regret theory [19,20], disappointment theory [21,22], cumulative prospect theory (CPT) [13], third-generation prospect theory [14] and so on. Besides, some decision analysis theories considering multiple factors have been proposed [23–25]. Among these theories, CPT has been regarded as the most popular theory [14–17]. This is because CPT describes the DM's behavioral characteristics well and gives the calculation formulas on values and weights of potential outcomes. Since the formulas have features of clear logic and simple computation process, CPT has been widely used to solve various decision-making problems considering DM's behavior. Therefore, how to incorporate CPT into decision analysis in emergency response deserves more attention.

In this paper, we develop a decision analysis method based on CPT for solving the risk decision-making problem in emergency response. In decision analysis for emergency response, DM's behavioral characteristics are considered. Based on CPT, the value of negative effect and weight of probability of each response result are calculated, respectively. Then, the prospect value of each candidate response action is calculated by aggregating the obtained values and weights. Further, an overall prospect value of each candidate response action can be assessed by aggregating the prospect value and cost of each action. Thus, a ranking of all candidate response actions can be determined according to the obtained overall prospect values.

The rest of this paper is arranged as follows. Section 2 gives a brief description of CPT. Section 3 gives the formulation and the solution procedure of the risk decision-making problem in emergency response. Section 4 presents a risk decision analysis method based on CPT. Section 5 gives an example based on the background of emergency evacuation from barrier lake downstream villages, and the example is used to illustrate the feasibility and validity of the proposed method. Lastly, Section 6 summarizes and highlights the main features of this paper.

2. Cumulative prospect theory (CPT)

Cumulative prospect theory (CPT) was proposed by Tversky and Kahneman [13]. It is a descriptive theory for human decision behavior under risk and uncertainty, and can be regarded as a combination of the original prospect theory [12] and the rank dependent expected utility model [18]. CPT is briefly described below.

We suppose a gamble is composed of n potential monetary outcomes $x_1,x_2,\ldots,x_n$ with probabilities $p_1,p_2,\ldots,p_n$, where x_i is the ith potential outcome and p_i is the probability of potential outcome x_i, $i=1,2,\ldots,n$. To assess the value of the gamble in cognitive psychology, a ranking of the n outcomes from the greatest to the smallest is determined, noted as $x_{(1)} \geq \ldots \geq x_{(t)} \geq 0 \geq x_{(t+1)} \geq \ldots \geq x_{(n)}$. In the obtained ranking, $x_{(k)}$ denotes the kth greatest one among the n potential outcomes, $k \in \{1,2,\ldots,n\}$; 0 denotes the outcome if the person will not joint in the gamble, which can be treated as the reference point. According to the obtained ranking of potential outcomes, probabilities $p_1,p_2,\ldots,p_n$ are re-indexed as $p_{(1)},p_{(2)},\ldots,p_{(n)}$, where $p_{(k)}$ denotes the probability of potential outcome $x_{(k)}$, $k \in \{1,2,\ldots,n\}$. Thus, the prospect value of the gamble is given by [13–17]

$$V = \sum_{k=1}^{t} v(x_{(k)})\pi^{+}_{(k)} + \sum_{k=t+1}^{n} v(x_{(k)})\pi^{-}_{(k)} \tag{1}$$

where $v(x_{(k)})$ is the value of potential outcome $x_{(k)}$; $\pi^{+}_{(k)}$ is the decision weight for the value of potential gain $x_{(k)}$, $k=1,2,\ldots,t$; $\pi^{-}_{(k)}$ is the decision weight for the value of potential loss $x_{(k)}$, $k=t+1,j+2,\ldots,n$. According to [13–17], $v(x_{(k)})$ can be represented by

$$v(x_{(k)}) = \begin{cases} x^{g}_{(k)}, & k=1,2,\ldots,j, \\ -\lambda(-x_{(k)})^{l}, & k=j+1,j+2,\ldots,n, \end{cases} \tag{2}$$

where g and l are exponent parameters, and λ is the loss aversion parameter. For $0<g<1$, the value function exhibits risk aversion over gains; for $0<l<1$, the function exhibits risk seeking over losses. The smaller g is, the greater risk aversion in the gain domain will be. Similarly, the smaller l is, the greater risk seeking in the loss domain will be. It has been widely recognized that loss-aversion factor λ should be greater than 1, which indicates that individuals are more sensitive to losses than gains. Usually, the values of parameters g, l and λ are determined through experiments [13,15,26–28].

The decision weights for gains and losses can be expressed as [13–17,29,30]

$$\pi^{+}_{(k)} = w^{+}\left(\sum_{j=1}^{n} p_{(j)}\right) - w^{+}\left(\sum_{j=k+1}^{n} p_{(j)}\right) \tag{3}$$

$$\pi^{-}_{(k)} = w^{-}\left(\sum_{j=1}^{k} p_{(j)}\right) - w^{-}\left(\sum_{j=1}^{k-1} p_{(j)}\right) \tag{4}$$

where $w^{+}(\cdot)$ and $w^{-}(\cdot)$ denote the weighting functions for gains and losses, respectively, and they are given by [13,15,29,30]

$$w^{+}(p) = \frac{p^{\chi}}{[p^{\chi}+(1-p)^{\chi}]^{1/\chi}} \tag{5}$$

$$w^{-}(p) = \frac{p^{\delta}}{[p^{\delta}+(1-p)^{\delta}]^{1/\delta}} \tag{6}$$

where χ and δ are model parameters. $w^{+}(\cdot)$ and $w^{-}(\cdot)$ are monotonic and exhibit inverse S-shapes for $0.27<\chi$, $\delta<1$. They are adequate for average decision-making behavior (i.e., overweight the outcomes with low probabilities and underweight the outcomes with moderate and high probabilities) [13,15,29,30]. Specially, if $\chi=\delta=1$, then $\pi^{+}_{(k)}=\pi^{-}_{(k)}=P_{(k)}$, i.e., the decision weights are equal to physical probabilities. The values of parameters χ and δ can also be determined through experiments [13,15,29,30].

3. The risk decision-making problem in emergency response and solution procedure

This section briefly describes the formulation and solution procedure of risk decision-making problem in emergency response.