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Research Article

A Regret Theory-Based Decision-Making Method for Urban Rail Transit in Emergency Response of Rainstorm Disaster

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The decision-making for urban rail transit emergency events takes an important role in both reducing the losses caused by disasters and ensuring the safety of passengers. For the rainstorm emergency decision-making without certain scenario prediction information, considering the characteristic that the predisaster prevention measures will influence the effect of in-process countermeasures, this paper aimed to analyze the whole process scenarios for the occurrence, evolution, and development of rainstorm disaster in urban rail transit by considering the regret aversion of the decision makers. An emergency decision-making method for the beforehand-ongoing two stages rainstorm emergencies was developed to assess the emergency decision-making of urban rail transportation in different rainfall flood scenarios. Besides, the utilities and application costs of the emergency plans are also considered when defining the optimal emergency decision-making. This paper purposes the emergency decision-making model based on regret theory to define the optimal predisaster prevention method and ongoing responding measure for different disaster scenarios. Taking the Tianjin rail transportation as an example, this paper defines the optimal emergency decision-making to respond typhoon "Lekima." The results show that if this method can be implemented in the rail transportation rainstorm disaster emergency responding and relevant disaster prevention management, then the reliability and risk responding capability of public transportation service can both be improved.

1. Introduction

Recently, with the fast increase of the economy and rapid growth of urban population in China, a series of problems has been generated, such as urban traffic congestion, frequent traffic accidents, and deterioration of travel environment [1]. To solve the above problems, the trip mode of public transportation, which is based on urban rail transit, has become an important choice [2]. Different from general public transportation, urban rail transit, as a public transport vehicle, operates traffic transportation within underground space and occupies less land resources [3]. At the same time, however, the closed design along the rail line makes the urban rail transit station as the only medium which can communicate with the outside. Once fault or accident occurs, it will not only affect the normal travel of passengers but will cause great negative impact on the production and normal living of the city [4].

Comparing with the ground transportation, once the construction of urban rail transit station and its underground space have been completed, it will own strong irreversibility due to the high difficulty of reconstruction. Especially, when urban rainstorm disasters happen, the back flow in the rail station entrance can be generated easily due to the urban waterlogging caused by heavy rain. The relevant equipment, electronic components, cables, and other electrical equipment will all be influenced, and the safe operation of rail transportation in underground space will also be influenced [5]. In August 2005, the torrential rain brought by the typhoon "Massa" caused the surface water back flow events in Shanghai Metro Line 1 (from the Changshu Road to Xujiahui Section), which influenced the normal operation of the train seriously. Thus, how to make an early warning and response to the rainstorm disaster in urban rail transit and how to minimize the losses have become an urgent task for both academics and the government departments [6–8].

Emergency decision-making is an important part of emergency management. It is a series of decision-making activities to respond to emergencies. When disasters or accidents happen or some omens of disaster occur and facing tough decision-making environment, emergency decision-making is a dynamic cycle process to make the emergency activity plan within limited time and maximize the realization of the emergency decision-making objectives. It not only involves the decision-making and respondence after emergencies, but also involves the identification and warning for various risk factors before emergencies happen [9]. In reality, the decision-making of rainstorm emergencies is generally restricted by the limited resources, time, and other constrains. It is possible that the selectable countermeasures and their effects during the events will be influenced by the predisaster prevention and mitigation measures. Thus, when conducting the emergency decision-making during beforehand-ongoing two stages, it is necessary to consider both the rainstorm disaster prevention measures before the event and the countermeasures during the event [10]. Facing the selection of rainstorm prevention measures, decision makers often own two types of expected regrets, which are the expected regret for cost waste caused by the over responding before the event and the expected regret for the casualties and property loss due to the insufficient response before the event [11]. Therefore, how to effectively analyze the whole process scenarios for the occurrence, evolution, and development of rainstorm disaster in urban rail transit, measure and weigh the two types of the expected regrets generated by the rainstorm disaster prevention, is the key point for the decision maker to design two-stage emergency decision-making plan, which contains disaster prevention before the event and the disaster scenario solutions during the event during the emergency decision-making process of the urban rail transit rainstorm disaster. It is also the key to rationally solve emergency decision-making problems with uncertain scenario prediction information before the event. Currently, the research on decision-making for emergency respondence has attracted the attention of some scholars. For the risk decision-making of the emergency respondence, Liu et al. proposed a risk decision-making method which is based on the analysis of fault tree [12]. Aiming at the risk decision-making that the attribute value and the state probability are both interval number information, Zhang et al. provided a calculation method for scheme regret value, which is applied to determine the rank of plans through establishing the optimization model to solve the maximal comprehensive perception utility of schemes [13]. Nian et al. developed a quantitative evaluation approach to assess the performance of an urban metro network. And they provide a theoretical foundation to explore the optimal assignment of newly built rail transit lines by considering network vulnerability [14]. Ding et al. studied the vulnerability of urban rail transit, and the results showed that the short turning route from Beixinjing to Longyang Rd. in Shanghai Metro Line 2 can effectively alleviate the overcrowding in the traffic demand area [15]. However, the existing researches mostly focus on the expected utilities of the one-time decision-making plans to select the plan, without considering the expected regrets of the plans. In fact, during the decision-making process, decision makers not only consider the expected utilities of emergency plans, but also consider the expected regrets of the overreaction, that is, the decision makers will compare expected regrets of overresponding and insufficient responding during the emergency responding process and then select the plan with larger expected utility and less expected regrets. Thus, for the emergency decision-making problems with undetermined scenario prediction information, decision makers often own two kinds of expected regrets: expected regret for overresponding and expected regret for insufficient responding. Based on the regret theory, this paper constructs the utility values of implementation effects of each countermeasure during the event when implementing different rainstorm prevention countermeasures before the event and different disaster scenarios happen during the event. Then, the optimal countermeasure can be determined from different disaster prevention solutions based on the utility value. Also, it can provide scientific basis for policy makers to prepare emergency plans. The contribution of this paper is to establish an emergency decision-making method during beforehand-ongoing two stages based on the regret theory. The proposed method considers the psychological behavior of human beings and is more suitable for the decision makers to analyze the whole process scenarios for the occurrence, evolution, and development of rainstorm disaster in urban rail transit.

The structure of the rest parts in this paper is as follows: Section 2 provides a literature review for the relevant research. Section 3 introduces the regret theory. Section 4 analyzes the rainstorm disaster emergency plan of rail transportation in Tianjin, China. Conclusions are drawn in the Section 5.

2. Literature Review

2.1. Research on Prevention and Control of Urban Rainstorm Waterlogging Disaster. The start of researches on prevention and control of rainstorm waterlogging and other meteorological disasters is early, and it has been gradually developed from engineering prevention measures to the new technology combing with the nonengineering measures. It emphasizes the application of disaster prevention and control system and the implementation of other types of technologies. By building the disaster comprehensive information platform and the establishment of emergency action system, the immediate emergency resolution for each urban disaster is achieved, and it highlights the high efficiency of observation, prevention, and emergency resolution for the whole process of the disaster within the combined action among advanced disaster information management technology, nonengineering measures, and engineering measures [16, 17]. Hernandez and Serrano proposed that the selection of mass original information can be conducted by applying the advanced collaborative knowledge management models to support emergency management, and it was simulated in Spanish flood emergency management [18]. Sherali et al. established a flood disaster model that is based on the transportation evacuation and applied it to flood emergency management in the Virginia Beach network [19]. By applying the system dynamics method, Simonovic and Ahmad established the victim evacuation model of flood emergency responding process and simulated the evacuation behaviors of the victims under emergency situation [20]. Chang et al. applied the scenario planning method to study the emergency logistics of flood disasters under uncertain conditions and provided a decision-making tool for government departments to schedule emergency materials [21]. Christopher explored the main threats and solutions to water supply, and the first reaction mechanism problems for sudden pollution events [22]. Tufekci and Wallace divided the impact of emergency management on floods into five parts, emphasizing that even the tiniest emergency preparation can have a meaningful impact on humans [23]. Mccarthy et al. considered that the utilization of hydrometeorology models to achieve risk communication between scientists and flood emergency managers is beneficial to flood disaster management, and real-time simulation experiments are conducted as a case of extreme flood event in the Thames, England [24]. Lang et al. integrated a multidisciplinary method containing geology, history, hydraulics, statistics, and so on, and they proposed a flood risk assessment method based on long-term historical flood data [25]. Sun and Guan used graph theory to measure the vulnerability of metro network, and the results showed that passenger flow, rainstorm, and other heavy weather are the key reasons for network vulnerability [4]. Sun et al. took Shanghai Metro as an example, and analyzed the vulnerability of urban rail transit networks by using complex network and graph theories [26]. Gattuso and Miriello used graphs and geographic indicators to compare and analyze the impact of storms and other disasters on the vulnerability of metro networks among 13 cities [27]. Derrible and Kennedy analyzed the relationship between metro network design and passengers ridership by using updated graph theory concepts, and they found that rainstorm and other heavy weather will attract passengers to use public transit [28]. Derrible and Kennedy used the constructed network indicators to conduct a comparative study of the subway systems in 33 cities, and analyzed the impacts from rainstorm and other natural disasters on the status, form, and structural characteristics of the rail transit network [29].

The flood disaster risk assessment method based on scenario simulation analysis can directly and accurately reflect the scope and extent of influence of disaster events, and it can provide some references for managers to prevent and mitigate disasters and make risk management decisions. However, at present, most of these methods just provide a fixed evaluation value statically to the risk, with less consideration for the uncertainties of the risk system itself and evaluation process. Therefore, it owns significant meanings to comprehensively consider the randomness, ambiguity, and other uncertainties of the risk evaluation, analyze the impact from uncertain factors on risk evaluation, gain the results and divisions of rainstorm disaster risk evaluation under different levels of the certainties, and then guide the disaster emergency management flexibly.

2.2. Research on the Risk Decision-Making Method for Emergency Respondence. In real life, the research on emergency respondence decision-making problem has achieved some certain research results [5, 30, 31]. Dillon et al. proposed a multiattribute risk decision-making method based on expected utility theory, aiming at the selection of respondence plan for terrorist attack [32]. Liu et al. proposed a risk decision-making method based on fault tree analysis for risk decision-making of emergency response [12]. For the selection of building reinforcement plans in uncertain earthquake disaster scenarios, Tamura et al. considered the characteristics of the decision makers that they emphasize small-probability but high-hazard events and constructed a utility function for evaluating different building reinforcement plans. Then, the reinforcement plans are ranked and optimized according to the utility of each building reinforcement plan [33]. Liu et al. considered the behavioral characteristics of decision makers such as reference dependence, loss aversion, etc; then, they proposed a risk decision-making method for emergency response based on cumulative prospect theory for emergency [34]. For evacuation problems after nuclear leaking events within the uncertain event scenario, Hämäläinen et al. constructed group utility function through collecting group opinions and then provided the optimal method of the accident emergency solution plan based on the multiattribute utility theory [35]. Weichselgartner and Kasperson conducted a case study from the field of vulnerability and resilience knowledge to research the differences of response strategies between different groups when facing disaster risks [36]. For the multitarget problems of postdisaster environment, Chiou and Lai studied the impact of natural disasters on infrastructure, and established the multitarget model of emergency rescue and traffic control based on the damage situation [37]. Akter and Simonovic proposed a multiobjective decision-making method based on fuzzy set theory and fuzzy logic for flood disaster emergency management [38]. Levy and Taji proposed an emergency plan selection method of group analytic network process, which aims at the emergency plan selection problems in the situation with incomplete information [39]. For the evacuation problems in emergencies, Stepanov and Smith proposed an optimal route allocation method based on integer programming, applied the M/G/c/c model of queuing theory to deal with the congestion and time delay problems in the path, and then evaluated the evacuation strategy [40]. Liu et al. took a fire and explosion accident in Tianjin Binhai New Area as an example, and they proposed a novel approach to emergency decision with hesitant fuzzy information, which takes regret aversion of the decision makers into account [41]. Zhang et al. studied the fuzzy multiattribute group decision-making problem with incomplete weight information, and proposed a group decision-making method that considers the decision makers' regret aversion [42].

For the decision-making method of emergency responding under uncertain scenario prediction information, current researches improved and developed the previous theories and methods of emergency decision-making. However, most of these researches focus on the single decision-making stage, such as the measure selection of disaster prevention and mitigation before the occurrence of the emergency, or the decision-making adjustment of the implemented measures. As the lack of assessment for emergency results, it is often constrained by both disaster resources and time when conducting real-life emergency decision-making. It is possible that the selective responding measures during the event and the results of these measures are influenced by the selected disaster prevention measures before the event. Based on that, decision makers will compare the results of proposed options within the possible outcomes of other options and select the plan that owns larger expected utility but lower expected regrets. Therefore, it is necessary to consider the decision maker's activity characteristics of regret aversion, study and design the beforehand-ongoing two-stage emergency respondence strategy of the disaster prevention and mitigation and the countermeasure during the events.

3. Regret Theory

3.1. Basic Concepts and Definitions. Regret theory is proposed by Bell [43] and Loomes and Sugden separately [44], which is used to explain the decision-making activity characteristics of decision makers. The basic thought of the regret theory is: decision makers often reflect on decisions which have already been made after the fact. If they have chosen other options, will the results be better now? If the answer is yes, the decision makers will feel regret inward; on the contrary, the decision makers will feel rejoiced. Therefore, when facing new decision-making problems, decision makers will generate an expected regret for alternative decision-making plans based on past experiences, and tend to choose the one which owns the smallest expected regret.

Let A_1 and A_2 present the two alternative plans, and x_1 and x_2 present the results of A_1 and A_2, separately. Without loss of generality, assume $x_1 \leq x_2$, then the perceptual utility of decision maker for plan A_1 can be presented as

$$u(x_1, x_2) = v(x_1) + R(v(x_1) - v(x_2)), \tag{1}$$

where $v(x_1)$ and $v(x_2)$ present the utilities that the decision makers gain from the results x_1 and x_2 and $R(v(x_1) - v(x_2))$ presents that the regret-rejoice value generated by the decision makers that only result x_1 without result x_2. If $R(v(x_1) - v(x_2)) < 0$, then it is regret value. If $R(v(x_1) - v(x_2)) > 0$, then it is rejoice value.

With reference to [45, 46], assume the functions $v(x)$ and $R(\Delta v)$ are

$$v(x) = x^{\alpha}, \tag{2}$$

$$R(\Delta v) = 1 - \exp(-\delta v). \tag{3}$$

In formula (2), α is the risk aversion coefficient, $0 < \alpha < 1$; less α means higher risk aversion extent. In formula (3), δ is the regret aversion coefficient of decision maker, $\delta > 0$; larger δ means that the regret aversion extent of decision maker is larger. From formulas (2) and (3), $v(x)$ and $R(\Delta v)$ are monotonically decreasing concave functions, which satisfy $v'(x) > 0$, $v''(x) < 0$ and $v(0) = 0$; $R'(\Delta v) > 0$, $R''(\Delta v) < 0$ and $R(0) = 0$. At the same time, if $\Delta v \leq 0$, then $R(\Delta v) \leq 0$, and $|\Delta v|$ is larger, $|R(\Delta v)|$ also is larger. This means that if the difference of the results between plan A_1 and plan A_2 is larger, then the perceptual regret from selecting plan A_1 to decision maker is also larger.

3.2. Description of the Decision Model. Considering the t_1 moment before the rainstorm, meteorological department gains some relevant information about the future rain probability, and predicts the rainstorm will happen in t_2 moment. Take $S = \{S_1, S_2, \ldots, S_n\}$ and $P = \{p_1, p_2, \ldots, p_n\}$ to present the n types of possible disaster scenarios and the probability of each disaster scenario through predication of rainstorm events. Besides, S_j is the possible j type scenario in t_2 moment, p_j presents the occurrence probability of S_j scenario, satisfies $\sum_{j=1}^{n} p_j = 1$, and $0 \leq p_j \leq 1$, $j = 1, 2, \ldots, n$. To reduce the negative influence of the rainstorm emergencies to the operation of rail transit, it is required to start the disaster prevention and mitigation measures in t_1 moment. Assume the operational m disaster prevention measure set is $A^1 = \{A_1^1, A_2^1, \ldots, A_m^1\}$ in t_1 moment, and A_i^1 presents the i disaster prevention measure in t_1 moment, $i = 1, 2, \ldots, m$. Assume the cost vector of the disaster prevention measure implementation is $C^1 = \{c_1^1, c_2^1, \ldots, c_m^1\}$, and c_i^1 presents the cost of disaster prevention measure A_i^1. Due to various constraints and restrictions on emergency resources and respondence lead time, in the situation of conducting different disaster prevention measures in t_1 moment, the alternative response measures of rainstorm in t_2 moment are different. Assume that the disaster prevention measure A_i^1 is conducted in t_1 moment, then there are m_i alternative respondence measures during the event in t_2 moment, as $A_i^2 = \{A_{i1}^2, A_{i2}^2, \ldots, A_{im_i}^2\}$. Besides, A_{ik}^2 presents that when applying the disaster prevention measure A_i^1 in t_1 moment, the alternative kth response measure in t_2 moment, $k = 1, 2, \ldots, m_i$. Correspondingly, the cost vector of each response measure in t_2 moment is $C_i^2 = \{c_{i1}^2, c_{i2}^2, \ldots, c_{im_i}^2\}$, and c_{ik}^2 presents the cost of the implementation of response measure A_{ik}^2 in t_2 moment. When conducting the selection of the prevent disaster countermeasure in time t_1 and the response countermeasure in time t_2, the set of q indicators of the emergency events responding results focused by decision makers is $I = \{I_1, I_2, \ldots, I_q\}$. Besides, I_l presents the lth indicator of responding results for the rainstorm emergency event focused by the decision maker, $l = 1, 2, \ldots, q$. Generally, decision-making problems involve two types of indicators: benefit indicator and cost indicator. Let I^B, I^C present the sets of benefit and cost separately, and satisfy $I^B \cup I^C = I$, $I^B \cap I^C = \varnothing$. Correspondingly, let L^B, L^C present the subscript sets of the benefit indicator and cost indicator separately, and satisfy $L^B \cup L^C = \{1, 2, \ldots, q\}$, $L^B \cap L^C = \varnothing$. The rainstorm emergency event responding result matrix for the uncertain prescenario predicting information with the twostage multiindicators is $D = [d_{ik}^{lj}]_{(m_1+m_2+\cdots+m_m)\times nq}$; besides, d_{ik}^{lj} presents the indicator value I_l of the responding results when conducting prevention measure A_i^1 in time t_1 and conducting responding measure A_{ik}^2 under scenario S_j in time t_2. Let $W = (\omega_C, \omega_1, \omega_2, \ldots, \omega_q)$ present the weight vector of the responding cost and multiindicators responding result from the responding measures during the event given by the decision maker in time t_2; besides, ω_C is the cost vector of the responding measure during the event for t_2 moment, ω_l is the vector for indicator I_l, and satisfies $\omega_C + \sum_{l=1}^{q} \omega_l = 1$, $0 \le \omega_C$, $\omega_l \le 1$.

To resolve the rainstorm emergency event responding decision-making in beforehand-ongoing two-stage, hysteron-proteron is applied. First, define the optimal responding measure in time t_2, and then define the optimal disaster prevention measure in time t_1 [10, 43–46].

Step 1. Calculate the standardized responding result matrix and standardized responding measure cost vector.

To mitigate the influence from different physical dimensions on the calculation results, standardize the responding result matrix $D = [d_{ik}^{lj}]_{(m_1+m_2+\cdots+m_m)\times nq}$, and then get the standardized responding result matrix $\overline{D} = [\overline{d}_{ik}^{lj}]_{(m_1+m_2+\cdots+m_m)\times nq}$, where

$$\overline{d}_{ik}^{lj} = \begin{cases} \dfrac{d_{ik}^{lj} - \min d^l}{\max d^l - \min d^l}, & l \in L^B, \\[2ex] \dfrac{\max d^l - d_{ik}^{lj}}{\max d^l - \min d^l}, & l \in L^C, \end{cases}$$

$$\max d^l = \max\left\{d_{ik}^{lj} \mid i = 1, 2, \ldots, m;\ k = 1, 2, \ldots, m_i;\ j = 1, 2, \ldots, n\right\},$$

$$\min d^l = \min\left\{d_{ik}^{lj} \mid i = 1, 2, \ldots, m;\ k = 1, 2, \ldots, m_i;\ j = 1, 2, \ldots, n\right\}. \tag{4}$$

Similarly, standardize cost vector of the each responding measure $C_i^2 = \left\{c_{i1}^2, c_{i2}^2, \ldots, c_{im_i}^2\right\}$ in time t_2, and get the standardized responding measure cost vector $\overline{C}_i^2 = \left\{\overline{c}_{i1}^2, \overline{c}_{i2}^2, \ldots, \overline{c}_{im_i}^2\right\}$, where

$$\overline{c}_{ik}^2 = \frac{\max c^2 - c_{ik}^2}{\max c^2 - \min c^2},$$

$$\max c^2 = \max\left\{c_{ik}^2 \mid i = 1, 2, \ldots, m;\ k = 1, 2, \ldots, m_i\right\}, \tag{5}$$

$$\min c^2 = \min\left\{c_{ik}^2 \mid i = 1, 2, \ldots, m;\ k = 1, 2, \ldots, m_i\right\}.$$

Step 2. Calculate the comprehensive utility V_{ik}^j when conducting responding measure A_{ik}^2 in time t_2.

Let v_{ik}^{lj} present conducting the disaster prevention measure A_i^1 in time t_1 and conducting the disaster prevention measure A_{ik}^2 to responding scenario S_j in time t_2, for the utility value of the responding result for indicator I_l. According to formula (2),

$$v_{ik}^{lj} = \left(\overline{d}_{ik}^{lj}\right)^{\alpha}. \tag{6}$$

Let v_{ik}^{C2} present cost utility value for conducting responding measure A_{ik}^2 during the event in time t_2, and the calculation formula is

$$v_{ik}^{C2} = \left(\overline{c}_{ik}^2\right)^{\alpha}. \tag{7}$$

According to v_{ik}^{lj} and v_{ik}^{C2}, comprehensive utility V_{ik}^j for conducing responding measure A_{ik}^2 in scenario S_j in time t_2 is

$$V_{ik}^j = v_{ik}^{C2}\omega_C + \sum_{l=1}^{q} v_{ik}^{lj}\omega_l. \tag{8}$$

Step 3. Define the optimal responding measure $A_{i\#}^{2j}$ when conducting measure A_i^1 in time t_1 and appearing scenario S_j in time t_2.

Let $V_{i\#}^{2j} = \max\left\{V_{i1}^j, V_{i2}^j, \ldots, V_{im_i}^j\right\}$, $V_{i\#}^{2j}$ corresponding to responding measure $A_{i\#}^{2j}$; besides, $A_{i\#}^{2j} \in A_i^2 = \{A_{i1}^2, A_{i2}^2, \ldots, A_{im_i}^2\}$ is the optimal responding measure in time t_2 when conducting measure A_i^1 in time t_1 and appearing scenario S_j in time t_2.

Step 4. Calculate the cost utility v_i^{C1} when conducting measure A_i^1 in time t_1.

To standardize the cost vector of disaster prevention measure, $C^1 = \{c_1^1, c_2^1, \ldots, c_m^1\}$. Then, get the standardized cost vector $\overline{C}^1 = \{\overline{c}_1^1, \overline{c}_2^1, \ldots, \overline{c}_m^1\}$, where

$$\overline{c}_i^1 = \frac{\max c^1 - c_i^1}{\max c^1 - \min c^1},$$

$$\max c^1 = \max\left\{c_i^1 \mid i = 1, 2, \ldots, m\right\}, \tag{9}$$

$$\min c^1 = \min\left\{c_i^1 \mid i = 1, 2, \ldots, m\right\}.$$

Let v_i^{C1} present the cost utility for conducting disaster prevention measure A_i^1 in time t_1, then the calculation formula is as follows:

$$v_i^{C1} = \left(c_i^1\right)^{\gamma}. \tag{10}$$

Step 5. Calculate the overresponding expected regret $r_{ii'}^1$ and insufficient responding expected regret $r_{ii'}^2$ for conducting measure $A_{i'}^1$, compared to conduct measure A_i^1. Then, establish overresponding expected regret matrix $R^1 = [r_{ii'}^1]_{m\times m}$ and insufficient responding expected regret matrix $R^2 = [r_{ii'}^2]_{m\times m}$, and build the comprehensive expected regret matrix $R = [r_{ii'}]_{m\times m}$.

For the selection of predisaster prevention measures, decision makers generally own two types of expected regrets, which are the expected regret for amount of cost waste due to overresponding and the expected regret for casualties or vehicle equipment damage due to insufficient responding before the event. Considering the two predisaster prevention measures A_i^1 and $A_{i'}^1$, $i \ne i'$. According to formula (10), the cost utilities for conducting disaster-prevention measures A_i^1 and A_i^1 in time t_1 are, respectively, v_i^{C1} and $v_{i'}^{C1}$. According to the thought based on regret theory, if $v_i^{C1} < v_{i'}^{C1}$, compared to conduct measure $A_{i'}^1$, there are expected regrets of overresponding to conduct measure A_i^1. Let $r_{ii'}^1$ present the expected regret of overresponding to conduct measure A_i^1, compared to conduct measure $A_{i'}^1$. According to formula (2), $r_{ii'}^1$ can be calculated with the following formula:

$$r_{ii'}^1 = \begin{cases} 1 - \exp\left[-\delta\left(v_i^{C1} - v_{i'}^{C1}\right)\right], & v_i^{C1} \le v_{i'}^{C1}, \\ 0, & v_i^{C1} > v_{i'}^{C1}. \end{cases} \quad (11)$$

For predisaster prevention measures A_i^1 and $A_{i'}^1$, there are expected regrets for casualties or vehicle equipment damage due to the insufficient responding before the event. If the disaster-prevention measure A_i^1 is conducted in time t_1 and scenario S_j appears in time t_2, then the optimal responding measure is $A_{i\#}^{2j}$ in time t_2, and the corresponding utility is $V_{i\#}^{2j}$; if the disaster-prevention measure $A_{i'}^1$ is conducted in time t_1 and scenario S_j appears in time t_2, then the optimal responding measure is $A_{i'\#}^{2j}$ in time t_2, and the corresponding utility value is $V_{i'\#}^{2j}$. Therefore, if the scenario S_j appears in time t_2, then compared to conduct measure $A_{i'}^1$, the expected regret of insufficient responding for conducting measure $A_{i'}^1$ can be presented as

$$r_{ii'}^{2j} = \begin{cases} 1 - \exp\left[-\delta\left(V_{i\#}^{2j} - V_{i'\#}^{2j}\right)\right], & V_{i\#}^{2j} \le V_{i'\#}^{2j}, \\ 0, & V_{i\#}^{2j} > V_{i'\#}^{2j}. \end{cases} \quad (12)$$

Thus, compared to conduct measure $A_{i'}^1$, the expected regret of insufficient responding for conducting measure A_i^1 is

$$r_{ii'}^2 = \sum_{j=1}^{n} r_{ii'}^{2j} p_j. \quad (13)$$

According to the calculation result from formulas (11)–(13), expected regret matrix for overresponding $R^1 = [r_{ii'}^1]_{m\times m}$ and expected regret matrix for insufficient responding $R^2 = [r_{ii'}^2]_{m\times m}$ before the event can be established, and then the comprehensive expected regret matrix of disaster prevention measure selection can be established as $R = [r_{ii'}]_{m\times m}$. In addition, $r_{ii'}$ is the comprehensive expected regret for conducting measure A_i^1 when compared to conduct measure $A_{i'}^1$. The calculation formula is

$$r_{ii'} = \beta r_{ii'}^1 + (1-\beta) r_{ii'}^2. \quad (14)$$

For this formula, β presents the expected regret weight of overresponding, which satisfies $0 \le \beta \le 1$. According to formulas (3), (11), and (12), in comprehensive expected regret matrix $r_{ii'} \le 0$. $r_{ii'}$ also presents the comprehensive expected regret value of measure A_i^1, compared to measure $A_{i'}^1$, and the comprehensive expected rejoice value of measure $A_{i'}^1$. Therefore, the less row and absolute value of element for measure A_i^1 in comprehensive expected regret matrix $R = [r_{ii'}]_{m\times m}$, the better measure A_i^1, which means the less $\sum_{i'=1}^{m} |r_{ii'}|$, the better measure A_i^1; correspondingly, the larger column and absolute value of element for measure A_i^1, then the better measure A_i^1, which means the less $\sum_{i'=1}^{m} |r_{i'i}|$, the better measure A_i^1.

Step 6. Calculate the overall expected rejoice value $\Phi^+(A_i^1)$ of measure A_i^1, the overall expected regret value $\Phi^-(A_i^1)$ of measure A_i^1, the rank value $\Phi(A_i^1)$ of measure A_i^1, and define the optimal responding measure based on the rank value.

According to the thought of PROMETHEE II [47, 48], let $\Phi^+(A_i^1)$ present the overall expected rejoice value of measure A_i^1, $\Phi^-(A_i^1)$ present the overall expected regret value of measure A_i^1, and $\Phi(A_i^1)$ present the rank value of measure A_i^1, then the calculation formula is

$$\Phi^+\left(A_i^1\right) = \frac{1}{m-1} \sum_{i'=1}^{m} \left|r_{i'i}\right|, \quad (15)$$

$$\Phi^-\left(A_i^1\right) = \frac{1}{m-1} \sum_{i'=1}^{m} \left|r_{ii'}\right|, \quad (16)$$

$$\Phi\left(A_i^1\right) = \Phi^+\left(A_i^1\right) - \Phi^-\left(A_i^1\right). \quad (17)$$

The larger $\Phi(A_i^1)$, the better measure A_i^1. Thus, according to the value of $\Phi(A_1^1), \Phi(A_2^1), \ldots, \Phi(A_m^1)$ from large to small, the rank of disaster prevention measure can be defined, and the optimal disaster prevention measure A_*^1 can be defined. And Figure 1 is shown to describe the process of the proposed method.

4. Case Study

4.1. The Selection of Research Area. Tianjin is one of the four municipalities in China, located in North China. It faces the Bohai Sea in the east and Yanshan Mountain in the north, locating in the downstream of Haihe River and crosses the banks of Haihe River. The terrain of Tianjin is dominated by plains and depressions and the elevation gradually decreases from north to south. As of 2018, the city has jurisdiction over 16 districts with a total area of 11,916.85 square kilometers. The built-up area is 1007.91 square kilometers and the resident population is 155.96 million.

The Tianjin Metro was built in the 1970s and is the second city in China to have an urban rail transit system after Beijing. In 2001, in order to build a modern transportation system for international metropolises, the upgrading and reconstruction of existing subway lines in Tianjin was officially launched, and the entire line was reopened and reoperated in 2006. After more than ten years of construction, as of the end of 2018, there are 6 urban rail transit lines in Tianjin, including subway lines 1, 2, 3, 5, 6, and 9. The network covers 10 municipal districts with an operating mileage of 219 kilometers. There are 156 stations (Figure 2), and the daily average passenger flow is about 1.2 million.

Located in the north temperate zone of the Eurasian continent, Tianjin is mainly dominated by the monsoon circulation. It is a region where the East Asian monsoon prevails, and belongs to a warm temperate semihumid monsoon climate with hot summers and concentrated rain. Precipitation for June, July, and August accounts for about

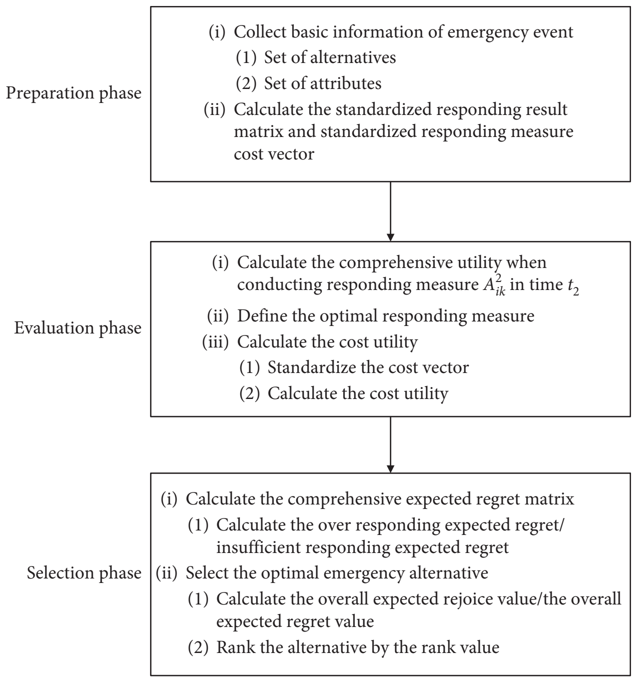

Figure 1: The decision-making process with the proposed method.

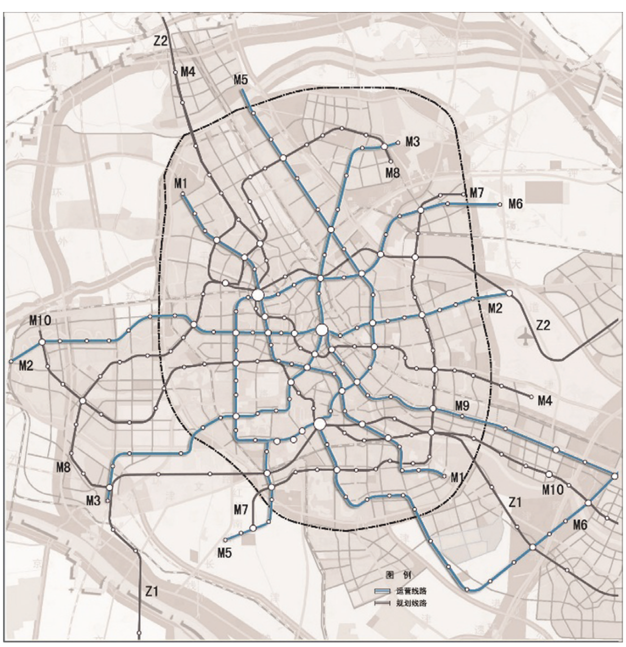

Figure 2: The urban rail transit line planning network of Tianjin in 2020.

75% of precipitation in the whole year. Heavy rains with daily precipitation of 50 mm and above mainly occur from July to August. Short-term and extremely heavy rainstorms are likely to cause serious economic losses and casualties in areas with low terrain, dense water systems or poor drainage, and cause other secondary and symbiotic disasters.

4.2. Emergency Decision-Making of Rail Transit Storm under the Influence of Typhoon "Lekima". On August 11, 2019, the meteorological department predicted that the typhoon "Lekima" would land in the Bohai Sea, resulting in heavy rain (100–240 mm) in Tianjin in a short period of time. It is easy to cause severe waterlogging in urban low-lying areas, concave overpasses, underground tracks, underground shopping malls and garages, and other underground spaces. Affected by many factors such as the rainfall caused by the typhoon and the location of the platform, there might be four situations: "no water accumulation at the subway entrance and exit," "a small amount of water accumulated in the subway entrance and exit, but not flooded into the entrance and exit," "rain flooding to the entrance and exit platform," and "rain water pouring into the platform." Through the field survey and analysis of meteorological experts, it is expected that the probability of the above four situations in the rail transit station area is $P = (0.4, 0.45, 0.1, 0.05)$ in the future.

In order to effectively respond the rainstorm emergency caused by the typhoon, the emergency management department prepared to implement disaster prevention measures in time t_1, and conducted the corresponding measure based on the certain disaster scenario caused by rainstorm in time t_2. The selective disaster prevention measures in time t_1 are

A_1^1: do not take any rain protection measure; the cost is $c_1^1 = 0$

A_2^1: place rainproof sandbags at the station entrance and exit; the cost is $c_2^1 = 2$ million dollar

A_3^1: place rainproof sandbags at the station entrance and exit, and prepare small pumps; the cost is $c_3^1 = 5$ million dollars

A_4^1: place rainproof sandbags at the station entrance and exit, prepare large pumps, and close the subway operation; the cost is $c_4^1 = 30$ million dollars

At the situation that the measure A_1^1 has been conducted in time t_1, according to the specific situation with the rainfall in time t_2, the selective responding measures are

A_{11}^2: do not take any rain protection measure; the cost is $c_{11}^2 = 0$

A_{12}^2: quickly adjust rainproof sandbags from other regions; the cost is $c_{12}^2 = 4$ million dollars

A_{13}^1: quickly adjust rainproof sandbags and small pumps from other regions; the cost is $c_{13}^2 = 8$ million dollars

A_{14}^1: quickly adjust rainproof sandbags and large pumps from other regions, and close the subway operation; the cost is $c_{14}^2 = 55$ million dollars

At the situation that the measure A_2^1 has been conducted in time t_1, according to the specific situation with the rainfall in time t_2, the selective responding measures are

A_{21}^2: do not take any rain protection measure; the cost is $c_{21}^2 = 0$

A_{22}^1: quickly adjust small pumps from other regions; the cost is $c_{22}^2 = 5$ million dollars

A_{23}^1: quickly adjust large pumps from other regions and close the subway operation; the cost is $c_{23}^2 = 50$ million dollars

At the situation that the measure A_3^1 has been conducted in time t_1, according to the specific situation with the rainfall in time t_2, the selective responding measures are

A_{31}^2: do not take any rain protection measure; the cost is $c_{31}^2 = 0$

A_{32}^1: quickly adjust large pumps from other regions and close the subway operation; the cost is $c_{32}^2 = 40$ million dollars

At the situation that the measure A_4^1 has been conducted in time t_1, according to the specific situation with the rainfall in time t_2, the selective responding measures are

A_{41}^2: do not take any rain protection measure; the cost is $c_{41}^2 = 0$

When conducting emergency measure selection, the decision maker mainly considers the following three indicators:

I_1: number of people injured. This indicator presents the number of injured (unit: people) that if a specific situation appears in a rail transit station, conducting measure A_i^1 in time t_1 and conducting measure A_{ik}^2 in time t_2. This indicator is cost indicator.

I_2: economic loss. This indicator presents the economic loss (unit: ten thousand dollar) of the rail transportation department that if a specific situation appears in a rail transit station, conducting measure A_i^1 in time t_1 and conducting measure A_{ik}^2 in time t_2. This indicator is cost indicator.

I_3: travel influence. This indicator presents the travel influence on passengers that if a specific situation appears in a rail transit station, conducting measure A_i^1 in time t_1 and conducting measure A_{ik}^2 in time t_2. It can be judged through scoring from 0 to 9 from experts and then provide the evaluation information. This indicator is cost indicator.

According to the judgement from the experts, responding result matrix can be defined as Table 1. The weight vector of the responding cost of responding measure selection during the event and the multiindicator responding results given by the decision maker in time t_2 is $W = (\omega_C, \omega_1, \omega_2, \omega_3) = (0.2, 0.4, 0.3, 0.1)$, and the weight of expected regret of overresponding and insufficient responding given by the decision maker is $\beta = 0.2$, $1 - \beta = 0.8$.

Table 1: Responding result matrix.

A_i^1	A_{ik}^2	I_1				I_2				I_3			
		S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
A_1^1	A_{11}^2	0	120	210	300	0	1500	2400	3800	0	2	6	9
	A_{12}^2	0	50	110	170	0	1100	1800	2400	1	5	9	7
	A_{13}^2	0	50	80	130	0	800	1400	1700	4	8	7	6
	A_{14}^2	0	50	80	100	0	800	1100	1500	7	6	4	3
A_2^1	A_{21}^2	0	0	60	130	0	0	1400	2000	2	6	9	7
	A_{22}^2	0	0	40	100	0	0	1100	1700	5	9	8	7
	A_{23}^2	0	0	40	100	0	0	900	1500	8	7	5	4
A_3^1	A_{31}^2	0	0	0	50	0	0	0	1300	4	9	7	6
	A_{32}^2	0	0	0	20	0	0	0	700	6	8	7	6
A_4^1	A_{41}^2	0	0	0	0	0	0	0	0	9	7	7	5

(1) Calculate the standardized responding result matrix and standardized responding measure cost vector.

According to formula (4), calculate the standardized responding result matrix as Table 2.

According to formula (5), define the standardized responding measure cost vectors as $\overline{C}_1^2 = (1, 0.927, 0.855, 0)$, $\overline{C}_2^2 = (1, 0.909, 0.091)$, $\overline{C}_3^2 = (1, 0.273)$, $\overline{C}_4^2 = (1)$ in time t_2.

(2) Calculate the comprehensive utility V_{ik}^j of conducting responding measure A_{ik}^2 in time t_2.

According to formulas (6)–(8), calculate the comprehensive utility V_{ik}^j of conducting responding measure A_{ik}^2 in time t_2, which is presented in Table 3, $\alpha = 0.7$.

(3) Confirm the optimal responding measure $A_{i\#}^{2j}$ to conduct measure A_i^1 in time t_1 and the scenario S_j appears in time t_2.

According to the comprehensive utility V_{ik}^j in Table 3, the optimal measure can be defined when conducting measure A_i^1 in time t_1 and scenario S_j appears in time t_2, which is presented in Table 4.

(4) Calculate the cost utility v_i^{C1} conducting measure A_i^1 in time t_1.

According to formulas (9) and (10), calculate the cost utility v_i^{C1} conducting measure A_i^1 in time t_1, let $\gamma = 0.8$. Then, $v_1^{C1} = 1$, $v_2^{C1} = 0.946$, $v_3^{C1} = 0.864$, and $v_4^{C1} = 0$.

(5) Calculate the overresponding expected regret $r_{ii'}^1$ and the insufficient responding expected regret $r_{ii'}^2$ for conducting measure A_i^1, comparing to conduct measure $A_{i'}^1$. Then, the expected regret matrix $R^1 = [r_{ii'}^1]_{m\times m}$ of overresponding and the expected regret matrix $R^2 = [r_{ii'}^2]_{m\times m}$ of insufficient responding can be both established. Also, the comprehensive expected regret matrix can be established as $R = [r_{ii'}]_{m\times m}$.

According to the formulas (11)–(13), calculate and establish the overresponding expected regret matrix $R^1 = [r_{ii'}^1]_{m\times m}$ and the insufficient responding expected regret matrix $R^2 = [r_{ii'}^2]_{m\times m}$ for the selected responding measure in time t_1, parameter value of the regret function is $\delta = 0.3$. Moreover, according to the expected regret matrixes of both overresponding and insufficient responding, the comprehensive expected regret matrix $R = [r_{ii'}]_{m\times m}$ for the selected responding measure in time t_1.

Table 2: Standardized responding result matrix.

A_i^1	A_{ik}^2	I_1				I_2				I_3			
		S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
A_1^1	A_{11}^2	1.00	0.60	0.30	0.00	1.00	0.61	0.37	0.00	1.00	0.78	0.33	0.00
	A_{12}^2	1.00	0.83	0.63	0.43	1.00	0.71	0.53	0.37	0.89	0.44	0.00	0.22
	A_{13}^2	1.00	0.83	0.73	0.57	1.00	0.79	0.63	0.55	0.56	0.11	0.22	0.33
	A_{14}^2	1.00	0.83	0.73	0.67	1.00	0.79	0.71	0.61	0.22	0.33	0.56	0.67
A_2^1	A_{21}^2	1.00	1.00	0.80	0.57	1.00	1.00	0.63	0.47	0.78	0.33	0.00	0.22
	A_{22}^2	1.00	1.00	0.87	0.67	1.00	1.00	0.71	0.55	0.44	0.00	0.11	0.22
	A_{23}^2	1.00	1.00	0.87	0.67	1.00	1.00	0.76	0.61	0.11	0.22	0.44	0.56
A_3^1	A_{31}^2	1.00	1.00	1.00	0.83	1.00	1.00	1.00	0.66	0.56	0.00	0.22	0.33
	A_{32}^2	1.00	1.00	1.00	0.93	1.00	1.00	1.00	0.82	0.33	0.11	0.22	0.33
A_4^1	A_{41}^2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.22	0.22	0.44

Table 3: Comprehensive utility of conducting responding measure A_{ik}^2 for scenario S_j in time t_2.

A_i^1	A_{ik}^2	S_1	S_2	S_3	S_4
A_1^1	A_{11}^2	1.000	0.775	0.568	0.200
	A_{12}^2	0.982	0.835	0.672	0.596
	A_{13}^2	0.945	0.807	0.753	0.692
	A_{14}^2	0.735	0.653	0.624	0.588
A_2^1	A_{21}^2	0.984	0.946	0.760	0.681
	A_{22}^2	0.944	0.887	0.807	0.721
	A_{23}^2	0.759	0.772	0.704	0.616
A_3^1	A_{31}^2	0.966	0.900	0.935	0.822
	A_{32}^2	0.827	0.802	0.815	0.768
A_4^1	A_{41}^2	0.900	0.935	0.935	0.957

Table 4: The optimal responding measure when conducting measure A_i^1 in time t_1 and scenario appears in time t_2.

A_i^1	S_1	S_2	S_3	S_4
A_1^1	A_{11}^2	A_{12}^2	A_{13}^2	A_{13}^2
A_2^1	A_{21}^2	A_{21}^2	A_{22}^2	A_{22}^2
A_3^1	A_{31}^2	A_{31}^2	A_{31}^2	A_{31}^2
A_4^1	A_{41}^2	A_{41}^2	A_{41}^2	A_{41}^2

$$R^1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.016 & 0 & 0 & 0 \\ -0.042 & -0.025 & 0 & 0 \\ -0.350 & -0.328 & -0.296 & 0 \end{bmatrix},$$

$$R^2 = \begin{bmatrix} 0 & -0.017 & -0.016 & -0.023 \\ -0.002 & 0 & -0.005 & -0.008 \\ -0.004 & -0.008 & 0 & -0.007 \\ -0.012 & -0.012 & -0.008 & 0 \end{bmatrix}, \quad (18)$$

$$R = \begin{bmatrix} 0 & -0.014 & -0.013 & -0.019 \\ -0.005 & 0 & -0.004 & -0.006 \\ -0.012 & -0.012 & 0 & -0.005 \\ -0.080 & -0.075 & -0.066 & 0 \end{bmatrix}.$$

(6) Calculate the overall expected rejoice value $\Phi^+(A_i^1)$ of measure A_i^1, the overall expected regret value $\Phi^-(A_i^1)$ of measure A_i^1, rank value $\Phi(A_i^1)$ of measure A_i^1, and define the optimal responding measure based on the rank value.

According to formulas (15)–(17), the overall expected rejoice value, overall expected regret value, and the rank value of measure A_i^1 can be calculated separately, which are as follows:

$$\Phi^+(A_1^1) = 0.032, \quad \Phi^+(A_2^1) = 0.034, \quad \Phi^+(A_3^1) = 0.028, \quad \Phi^+(A_4^1) = 0.010;$$

$$\Phi^-(A_1^1) = 0.015, \quad \Phi^-(A_2^1) = 0.005, \quad \Phi^-(A_3^1) = 0.010, \quad \Phi^-(A_4^1) = 0.074;$$

$$\Phi(A_1^1) = 0.017, \quad \Phi(A_2^1) = 0.029, \quad \Phi(A_3^1) = 0.018, \quad \Phi(A_4^1) = -0.064;$$

According to the rank value $\Phi(A_i^1)$, the rank of disaster prevention measure for time t_1 can be defined, which is $A_2^1 \succ A_3^1 \succ A_1^1 \succ A_4^1$. Therefore, the optimal disaster prevention measure in time t_1 is A_2^1. In addition, measure A_{21}^2 is conducted in time t_2 within the scenario S_1 and S_2, and measure A_{22}^2 is conducted in time t_2 within scenario S_3 and S_4.

4.3. Comparative Analysis. In this section, we proposed two different decision-making methods and compared them with the regret theory to demonstrate the validity and feasibility of the proposed model. The first method (prospect theory) is based on bounded rationality and the second method (TOPSIS) is based on complete rationality [41]. Thus, we could compare the results from different methods [42]. The detailed calculation processes and parameter values of prospect theory and TOPSIS can be searched by reference [49–53]. Table 5 summarizes the ranking information for all alternatives by using these three decision-making methods.

Table 5 shows that the optimal alternative determined using proposed method was obviously different from that obtained by prospect theory and TOPSIS. The reason lies in the following aspects: firstly, compared with prospect theory and TOPSIS, regret theory has taken the expected utility of the plan and the expected regret of the overreaction into

Table 5: Ranking results by using three different decision-making methods.

Alternatives	Regret theory		Prospect theory		TOPSIS	
	Comprehensive value	Ranking order	Comprehensive value	Ranking order	Comprehensive value	Ranking order
A_1^1	0.017	3	0.159	2	0.333	4
A_2^1	0.029	1	−0.772	4	0.646	3
A_3^1	0.018	2	0.699	1	0.822	1
A_4^1	−0.064	4	−0.460	3	0.667	2

consideration; so, the decision makers will compare expected regrets of overresponding and insufficient responding during the emergency responding process and then select the plan with larger expected utility and less expected regrets. Secondly, as the proposed method considers the beforehand-ongoing two-stage rainstorm emergencies, it is possible that the selective response measures and the impact of the measure implementation will be influenced by the premeasures of disaster prevention and mitigation. Besides, the decision-making method based on prospect theory involves many parameters, so the uncertainties in the results may be amplified, and the calculation is complex. At the same time, according to this method, the information of specific reference points is required to gain from decision makers. It is difficult to get in generally [42]. The psychological behavior of the decision maker has not been considered and the evaluation of emergency event results are also limited in the decision-making method which is based on TOPSIS. Thus, the accuracy of evaluation will be affected [41]. So, the proposed method involves the psychological behavior of person. Compared with the assumption that the decision maker is completely rational, the proposed method can deal with the decision problem more reasonably, and is more suitable for the decision makers to analyze the whole process scenarios for the occurrence, evolution, and development of rainstorm disaster in urban rail transit.

5. Conclusion

Urban rail transit emergency decision-making is generated based on the new era background. The research on urban rail transit emergency decision-making is beneficial to ensure the safe travel of urban rail transit passengers and the safe operation of urban rail transit, and ultimately promote the healthy development of urban rail transit.

For the emergency responding decision-making without certain expected scenario information before the event, this paper proposes an emergency responding decision-making method during beforehand-ongoing two stages based on the regret theory. This method applies reverse-order method to conduct the analysis and define the optimal responding measure for predisaster prevention measure and disaster scenario during the event, through calculating the utility of responding measure conducting result in each event. Based on the thought of regret theory, overresponding expected regret and insufficient responding expected regret of any two predisaster prevention measures have been calculated separately. Furthermore, the rank of disaster prevention measures can be determined by calculating the overall expected rejoice value, overall expected regret value, and rank value of each disaster prevention measure. On this basis, it is possible to determine the optimal predisaster prevention measures and the win-win measures for possible disaster scenarios in each case. It can be used as a reference for emergency decision-making of sudden rainstorm within emergency management of urban rail transit.

Through the research of the emergency decision-making method for urban rail transit, this paper provides reference for urban rail transit emergency prearranged planning. But, it contains the following limitations. First, the weight determination in the emergency decision-making evaluation model established in this paper is mainly obtained through subjective evaluation, to reduce the subjective influence from experts. It is necessary to further strengthen the relevant statistic data in the analysis of rail transit emergency; thus, the determination of the weight of emergency decision-making indicators will be more objective. Second, the urban rail transit emergency decision-making is coped with the occurrence of urban rail transit rainstorm events. However, the occurrence of emergency events often contains certain principles and mechanisms. It is necessary to further study the principles and mechanisms of the occurrence of rainstorm emergency events, and then the accuracy of emergency decision-making can be improved significantly.

Data Availability

The numerical application data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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