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Safety management of waterway congestions under dynamic risk conditions- A case study of the Yangtze River

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Abstract: With the continuous increase of traffic volume in recent years, inland waterway transportation suffers more and more from congestion problems, which form a major impediment to its development. Thus, it is of great significance for the stakeholders and decision makers to address these congestion issues properly. Fuzzy Techniques for Order Preference by Similarity to an Ideal Solution (TOPSIS) is widely used for solving Multiple Criteria Decision Making (MCDM) problems with ambiguity. When taking into account fuzzy TOPSIS, decisions are made in a static scenario with fixed weights assigned to the criteria. However, risk conditions usually vary in real-life cases, which will inevitably affect the preference ranking of the alternatives. To make flexible decisions according to the dynamics of congestion risks and to achieve a rational risk analysis for prioritising congestion risk control options (RCOs), the cost-benefit ratio (CBR) is used in this paper to reflect the change of risk conditions. The hybrid of CBR and fuzzy TOPSIS is illustrated by investigating the congestion risks of the Yangtze River. The ranking of RCOs varies depending on the scenarios with different congestion risk conditions. The research findings indicate that some RCOs (e.g. “Channel dredging and maintenance”, and “Prohibition of navigation”) are more cost effective in the situation of a high level of congestion risk, while the other RCOs (e.g. “Loading restriction”, and “Crew management and training”) are more beneficial in a relatively low congestion risk condition. The proposed methods and the evaluation results provide useful insights for effective safety management of the inland waterway congestions under dynamic risk conditions.

Keywords: Fuzzy-TOPSIS, MCDM, dynamic analysis, waterway congestion, Yangtze River, maritime risk

1. Introduction

Inland waterway transportation, providing crucial linkages between domestic and international shipping markets, plays a significant role in promoting the economic development of many countries. At the end of 2013, the length of China’s inland navigation channel reached nearly 126 thousand kilometres, ranking number one in the world. For remaining its fast economic development, China relies much on the inland waterway transportation to promote the circulation of materials and economy among various industries from different regions. In addition, shipping through inland waterways is an irreplaceable transportation mode because of its low cost as well as low energy consumption compared to that of other modes. However, congestion problems in inland waterways inevitably increase the traffic density of channels, and reduce their navigational capacity and efficiency. The negative impacts become more and more serious in certain places along the Yangtze River such as harbour areas, dam areas, and lock areas. This has hindered the sustainable development of inland waterway shipping, as well as the economic development of the associated regions, triggering research needs in urgency.

Traffic congestion, characterized by slower speeds and longer time of queuing [1], is to some extents a reflection of contradictions between increasing traffic volume and limited transport capacity. The nature characteristics of channels themselves are immediate causes that constrain the transport capacity due to their insufficient navigable dimensions, small curvature radius and torrential currents, etc. Another influencing factor is the natural environment, such as gale, dry season, heavy fog and flooding, which may result in either congestions or suspension of shipping for a certain period. Bridges are one of the constructions on the water that can interrupt the vessel traffic by narrowing the channels and affecting the navigation to an extent. It is usually the reason of collisions between ships and bridges [2]. The insufficient navigational clearance due to bridge constraints makes it a man-made obstruction. In addition, inland waterways suffer from congestion problems especially in port and lock areas. The capacity problems in the field of port and lock operations are a constraint to inland waterway transportation, leading to the potential of business loss in container terminals [3] and huge delay costs for shipping in some lock areas [4]. Apart from the above reasons, accidents can contribute more to waterway congestions. Accidents such as ship grounding and untreated shipwrecking may not only cause congestions, but also damage the riverbed causing severe consequences [5]. On December 15th, 2004, a severe congestion resulting from several grounding accidents in the Yangtze River led to a complete block of the channel, in which more than 200 vessels were trapped in the river for more than one week [6].

The Yangtze River, known as the longest inland river in China, has its cargo throughput increment at a rate of more than 10% in recent years and reached 2.06 billion tons in 2014 - almost a six-fold increase compared to that a decade ago, which makes it the busiest navigable inland waterway in the world since 2006 [5]. As such a crucial inland waterway, congestion problems in the Yangtze River would cause more damage to its economic development than that of other areas. Given that, few studies were conducted in terms of avoiding, managing, and alleviating inland waterway congestions, and the lack of available and suitable theoretical guidance usually made it difficult for the stakeholders to react correctly and properly when a congestion occurs. Thus, it is of urgency and significance to develop countermeasures against inland waterway congestion risk, to assess their effect on congestion risk control, and to select the most optimal solutions to different risk conditions. The findings can provide the guidelines for the authorities and the decision makers to manage the congestion in a dynamic environment, and to guarantee the safe and efficient transport of freights through inland waterways. In a preliminary study [7], Safety Critical Factors (SCFs) influencing congestion was identified through correlation analysis of historical failure data and then a Congestion Risk Indexes (CRI) was introduced to assess the impacts of individual SCFs on the congestion risks based on a Bayesian Network (BN) model. This paper is conducted from a different perspective on safety management of congestion risk as the follow-up study. The contributions and novelties of this paper lie in the development of a series of practical and cost effective risk control options (RCOs) to manage the inland waterway congestions according to the past research, relevant regulations and in-depth discussion with domain experts. Besides, the traditional Fuzzy-TOPSIS method is extended by incorporating a new application of cost-benefit ratio to reflect decision makers' risk preference under different risk levels so as to achieve the dynamic evaluation of RCOs in different real scenarios. A case study of the Yangtze River is investigated to demonstrate the applicability of the proposed approach in the risk-based decision-making of RCOs for different congestion conditions.

The rest of this paper is organised as follows. Section 2 reviews the previous studies conducted on waterway congestion risk especially that of the Yangtze River to highlight the research gaps, and the research related to multiple-criteria decision making (MCDM) problems to discuss the advantages and explore the applicability of the hybrid method in this study. Section 3 describes the research steps and proposed methods to carry out evaluation of RCOs in different scenarios. The feasibility of using the proposed approach to prioritise the RCOs are analysed using a real case study of safety management of congestion risk in the Yangtze River in Section 4. The findings are further validated through a comparative study with other classical MCDM methods. The implications of the validated research outcomes are discussed with regard to dynamic risk environments in Section 5, and this paper is concluded in Section 6.

2. Literature review

In this section, the previous studies relating to the safety management of waterway congestion are first reviewed, followed by the introduction of the features and applications of various MCDM methods. It focuses on the justification of selecting right MCDM methods for the solution to waterway congestion management.

2.1. Waterway congestions

Various studies attempting to identify and handle waterway congestion risk were carried out from different aspects in the past few years. A simulation approach was one of the commonly used techniques in the field of waterway congestion study. Effects of congestions on the performance and investment of waterway systems were evaluated through a simulation model using demand elasticity relationship [8]. Yeo et al. [3] formulated a mathematical model to evaluate the marine traffic congestion in the North harbour of Busan port by using the AWE-SIM simulation program, so as to estimate the tendency of ship traffic conditions. Similar studies were conducted in European short sea shipping cases as well [9]. As the bottlenecks that constrain the development of waterway transport potential, ports and locks have been studied from numerous aspects, especially on waiting time which directly affects the strictly scheduled transportation service. A queuing analysis in terms of multiple types of interruptions was conducted to evaluate the average waiting time of vessels at the entrance of narrow waters, which has greater impact on the congestions in maritime traffic [10]. In this study, non-simultaneous and possibly simultaneous interruptions were considered in the case of the Strait of Istanbul to calculate the waiting time. The results showed the rationality of the model to approximate the expected waiting time and predict the impact of various factors on the congestion at a waterway entrance. Vessel traffic management systems in Europe inland waterways were assessed to tackle the problems of increasing waiting time at locks and inland ports due to traffic congestion and to explore the optimal use of the available capacity of inland shipping [11]. Valid trip data for inland waterway vessels were extracted from Automatic Identification System (AIS) in the Paducah for supporting analysis on port congestion in combination with other databases [12]. Besides, there was also research focusing on dealing with congestion issues from a management perspective. Three types of control alternatives were evaluated and compared for cost-effective lock control management under different congestion conditions [13]. Shippers' responses to transportation system congestions and performance were modelled on the most congested segment of the Upper Mississippi River to reveal its influence on the direct economic benefit related to congestion control measures [14]. Han et al. [15] developed an iterative improvement method to reduce the potential traffic congestion in a marine container transhipment hub as well as determine the storage locations of incoming containers.

More recently, research of traffic congestion in the Yangtze River mainly focussed on the qualitative analysis and design of safety management frameworks. Cai and Liu [16] discussed the use of an intelligent decision support system in inland river incident management to solve the problems related to congestion caused by ship grounding. Chen et al. [17] proposed a set of approaches for inland channel modelling, water surface generating and random vessel generating, in order to improve the efficiency and safety of the inland transport at dry seasons. Moreover, some management suggestions were proposed based on the qualitative analysis of some congested segments of the Yangtze River [18]. It is observed that few attempts have been made on the control measures of inland waterway congestion by using quantitative methods, fewer on the solutions when dynamic congestion risks are taken into account.

2.2. Multiple-criteria decision making methods

MCDM problems are frequently encountered in almost every aspect in real life. Various methods exist that can be applied to solve such problems. One of the well-known and widely-used techniques is the analytic hierarchy process (AHP) developed by Saaty [19]. AHP requires the decision makers to supply judgments about the relative importance of each pair of criteria and then specify a preference for each decision alternative against each criterion. It is appropriate for complex decisions involving the comparison of decision criteria that are difficult to quantify. It is flexible and intuitive, and has the ability to check consistencies of experts' judgements. However, the number of pair wise comparisons may become very large with the increasing of number of decomposed subsystems. Compared to AHP, the TOPSIS method is simpler in terms of the requirements of input data, based on the principle that the most suitable solution should be the closest to the positive ideal solution and the farthest from the negative ideal solution. It can take input as any number of criteria and attributes [20]. Within the context of compromise programming, many other MCDM ranking methods have been studied [21], such as VIKOR (VIsekriterijumska optimizacija i KOmpromisno Resenje) [22], the PROMETHEE (Preference Ranking Organization Methods for Enrichment Evaluation) [23], and the ELECTRE (Elimination Et Choice Translating Reality) [24]. All these traditional MCDM methods have their advantages and disadvantages which constrain their applications to specific real-world decision problems. For example, some errors would occur in multi-criteria optimization calculation in the traditional VIKOR method [25]. PROMETHEE suffered from the rank reversal problem when a new alternative was introduced. Besides, PROMETHEE-

I can only provide a partial ranking of the alternative [20]. One common weaknesses shared by the above-mentioned traditional MCDM methods is that the evaluation values obtained through them are precise, which is usually inadequate to model the real-life situation when input data is vague and uncertainty in data is high. Thus, the fuzzy set theory is often introduced and incorporated to deal with imprecise and vague information, making the traditional MCDM methods more applicable [26]. In addition, the combinations of different MCDM methods also provide feasible solutions to complex MCDM problems, including but not limited to, fuzzy TOPSIS [27], AHP-TOPSIS [28], fuzzy VIKOR [29], and fuzzy PROMETHEE [30].

As a well-established method, TOPSIS has been widely studied for several decades, and been applied in many different fields. In terms of its application related to congestion management, Awasthi et al [27] developed a set of criteria for sustainability evaluation of transportation system taking congestion reduction in city centres into consideration. Based on that, fuzzy TOPSIS was applied for the selection of best alternative according to judgments from three experts. In another study [28], TOPSIS was used with AHP to evaluate the actual status of urban road intersections traffic congestion, so as to provide a solution to traffic management. Applications of TOPSIS to similar problems can be also found in recent studies such as [31] and [32].

According to the previous studies, we choose fuzzy TOPSIS to evaluation the control measures of the congestion risk in inland waterways because [33]: A) TOPSIS can prioritize the selections considering two distances. This aids the decision makers to seek for not only the maximum benefits of managing inland waterway congestions, but also all for the minimum cost to achieve the goal. B) The method is intuitive, easy to understand and to implement. More importantly, the data collected from various sources involving risk, cost, social benefits, can fit better in the TOPSIS method than the other MCDM. It is so important for inland waterway authorities to realise an industrial implementation easily. C) It is able to manage each kind of variables and each type of criteria, and hence the performance is affected by the number of alternatives at a minimum level.

3. Methodology

The main steps developed to evaluate the cost effectiveness of RCOs under different risk levels are described below.

Step 1: The targeted RCOs are put forward according to the identified SCFs of the inland waterway congestions [7], and the model for cost-benefit analysis is established with respect to the evaluation criteria.

Step 2: The concept of cost-benefit ratio (CBR) is introduced to reflect the status of congestion risk and the relative weight of each criterion is decided based on the probabilities of relevant SCF contributing to inland waterway congestions.

Step 3: The fuzzy sets of cost and benefit criteria are formulated to convert the assessment grades obtained from the experts into quantitative fuzzy numbers using the defined membership functions. Then, these fuzzy numbers are normalised and weighted with regard to different criteria.

Step 4: The Fuzzy Positive Ideal Reference Point (FPIRP) and Fuzzy Negative Ideal Reference Point (FNIRP) are determined and the distances from each RCO to FPIRP and FNIRP are calculated. The closeness coefficient of each RCO is calculated and RCOs are ranked according to their closeness coefficients with respect to different congestion risk states.

Step 5: The evaluation results from fuzzy TOPSIS are compared with that obtained from other widely applied MCDM methods to verify the findings and discuss the superiority of the proposed method in solving waterway congestion problems.

3.1. Cost benefit analysis

Conducting cost-benefit analysis in terms of multiple RCOs is analogous to a MCDM problem. It means that ranking the RCOs and choosing the optimal one through the comprehensive evaluation of their cost effectiveness against different sets of cost and benefit criteria. As shown in Fig. 1, there are n cost criteria (C_1... C_n) and m benefit criteria (C_{n+1}... C_{n+m}) in the model, aiming at evaluating l RCOs in order to make the most cost-effective decision.

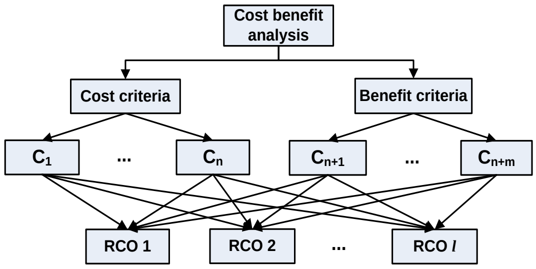

Fig. 1. Model of cost benefit analysis

In this paper, CBR refers to the ratio between importance of cost and benefit, which reflects the risk preference of demand of decision makers for low cost and/or high benefit under different congestion risk levels. Thus, by changing the value of CBR, different rankings of the RCOs are obtained and presented to reflect the influence of risk conditions on decision-making. Supposing that the importance degree (weight) of the cost is w_C and that of benefit is w_B, then the CBR can be presented by Eqs. (1) and (2).

$$CBR = \frac{C}{B} \tag{1}$$

and,

$$C + B = 1 \tag{2}$$

Consider Figure 1 as an illustration, if there are *m* cost criteria (C_1... C_m) and *n* benefits criteria (C_1... C_n), (the relative weight of each cost criterion is $w_1, \ldots, w_n$, $\sum_{p=1}^{n} w_p = 1$,while the relative weight of each benefit criterion is $w_{n+1}, \ldots, w_{n+m}$, $\sum_{q=n+1}^{n+m} w_q = 1$), then the relative weight of each criterion in the cost-benefit analysis model can be obtained using Eq. (3).

$$W_{C_i} = \begin{cases} C \times w_i & i \in [1, n] \\ B \times w_i & i \in [n+1, n+m] \end{cases} \quad (i = 1, 2, \ldots, n+m) \tag{3}$$

where W_i^C indicates the normalised weight of a cost criterion, while W_j^B indicates the weight of a benefit criterion.

3.2. Fuzzy sets

As the theoretical foundation of fuzzy logic, fuzzy set theory has been proved to be a useful mathematical tool to handle vagueness and uncertainty in a system [34], [35], which is proposed by Zadeh [36]. Being an extension to crisp set, a fuzzy set allows partial membership rather than total membership or non-membership, which maps element's degree of membership between 0 and 1 in the usual case [36]. In practical applications, linguistic estimation is converted into fuzzy numbers using fuzzy membership functions so as to evaluate quantitatively. In particular, the triangular fuzzy membership is a commonly used because of its effectiveness for promoting representation and processing imprecise information due to its computational simplicity [37].

A fuzzy set $\tilde{A}$ in a universe of discourse *X* is characterized by a membership function $\mu_{\tilde{A}}(x)$ that assigns each element *x* in *X* a real number in the interval [0, 1]. The corresponding relation between numeric values of fuzzy numbers and their degrees of membership can be represented by Eq. (4) [27].

$$\tilde{A}=\left\{\left[x,\mu_{\tilde{A}}(x)\right] \mid x\in X, 0\le \mu_{\tilde{A}}(x)\le 1\right\} \quad (4)$$

A Triangular Fuzzy Number (TFN) $\tilde{a}$ can be defined as a triplet (a_1, a_2, a_3), and the membership function is defined as:

$$\mu_{\tilde{a}}(x)=\begin{cases} 0, & if\ x\le a_1 \\ \dfrac{x-a_1}{a_2-a_1}, & if\ x\in(a_1,a_2) \\ 1, & if\ x=a_2 \\ \dfrac{a_3-x}{a_3-a_2}, & if\ x\in(a_2,a_3) \\ 0, & if\ x\ge a_3 \end{cases} \quad (5)$$

Where a_1 and a_3 represent the smallest and the largest possible values respectively of fuzzy number $\tilde{a}$, while a_2 is the most promising value that denotes a complete membership.

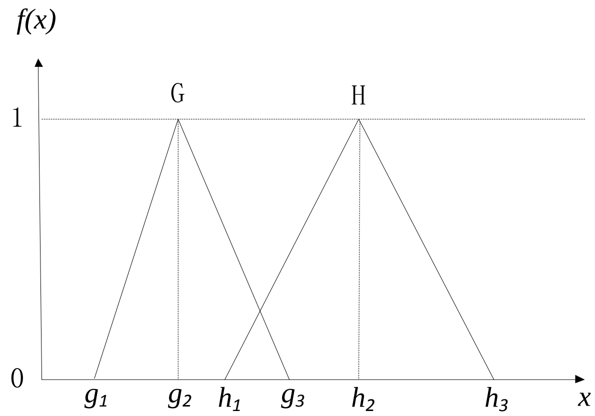

Fig. 2. Triangular membership functions $\tilde{G}(x)$ and $\tilde{H}(x)$

As shown in Fig. 2, consider two TFNs, g= (g_1, g_2, g_3) and h= (h_1, h_2, h_3), then the operations with these fuzzy numbers are defined as follows [38]:

$$\tilde{G}+\tilde{H}=(g_1,g_2,g_3)+(h_1,h_2,h_3)=(g_1+h_1,g_2+h_2,g_3+h_3) \quad (6)$$

$$\tilde{G}-\tilde{H}=(g_1,g_2,g_3)-(h_1,h_2,h_3)=(g_1-h_1,g_2-h_2,g_3-h_3) \quad (7)$$

$$\tilde{G}\times\tilde{H}=(g_1,g_2,g_3)\times(h_1,h_2,h_3)=(g_1\times h_1,g_2\times h_2,g_3\times h_3) \quad (8)$$

$$\tilde{G}/\tilde{H}=(g_1,g_2,g_3)/(h_1,h_2,h_3)=(\frac{g_1}{h_3},\frac{g_2}{h_2},\frac{g_3}{h_1}) \quad (9)$$

$$w\tilde{G}=w(g_1,g_2,g_3)=(wg_1,wg_2,wg_3),\ w>0 \quad (10)$$

3.3. Fuzzy TOPSIS method

The TOPSIS method is developed by Hwang and Yoon [39], modified by Hwang, Lai, and Liu [40] and is a classical MCDM method for identifying solutions from a finite set of alternatives. The basic principle is that the optimal alternative should have the shortest distance to the positive ideal solution and the farthest distance to the negative ideal solution. The positive ideal solution is a solution that maximises the benefit criteria and minimises the cost criteria, while the negative ideal solution does the contrary. Due to its sound logic, considerations for both positive and negative ideal solutions at the same time, as well as the easiness in understanding and implementation, TOPSIS have been widely accepted and used for tackling MCDM problems in real situations [41]. However, in the conventional TOPSIS method, expert's judgements are measured with crisp values, which is not always possible in many practical cases. Instead, the fuzzy TOPSIS method that uses linguistic values is developed to deal with MCDM problems in fuzzy environment [42-43], and is selected in this paper to rank the RCOs in different congestion risk levels.

The main steps to follow in fuzzy-TOPSIS method are described as follows.

(1) Choose the linguistic ratings for the RCOs in terms of cost-benefit criteria and convert linguistic evaluations into fuzzy numbers.

Assuming that, i^{th} criterion contain k ratings (H_1, H_2,…, H_k) which respectively corresponds to k TFNs, that are (g_1, h_1, p_1), (g_2, h_2, p_2),…, (g_k, h_k, p_k), and the brief degrees on ratings to j^{th} RCO from an expert are (B_1, B_2,…, B_k), with $\sum_{t=1}^{k} B_t = 1$. Then the fuzzy number of j^{th} RCO in terms of i^{th} criterion can be obtained using Eq. (11) [44] based on the operation rules described in Section 3.2. The scales used for rating will be described in Section 4.

$$r_{ji} = \left(g_{ji}, h_{ji}, p_{ji}\right) = \sum_{t=1}^{k} (g_t, h_t, p_t) \times B_t \tag{11}$$

Where r_{ji} denotes the fuzzy number of j^{th} RCO in terms of i^{th} criterion.

(2) Establish a fuzzy decision making matrix.

The fuzzy decision making matrix R is constructed in terms of n criteria and m RCOs.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad j = 1,2,\ldots m; i = 1,2,\ldots n \tag{12}$$

(3) Establish the normalised fuzzy decision matrix.

Linear scale transformation is applied to transform various criteria scales into a comparable plane. In this paper, the ratings of cost and benefit criteria are set in the same scale (as described in details in Section 4.3) so that they can be normalized simultaneously. The normalised fuzzy decision matrix $\tilde{R}$ can be obtained as follows:

$$\tilde{R} = \left[\tilde{r}_{ji}\right]_{m \times n} \tag{13}$$

$$\tilde{r}_{ji} = \frac{r_{ji}}{p_i^+} = \left(\frac{g_{ji}}{p_i^+}, \frac{h_{ji}}{p_i^+}, \frac{p_{ji}}{p_i^+}\right) \tag{14}$$

Where p_i^+ denotes the maximum value of upper limits of fuzzy numbers p in the i^{th} column of matrix $\tilde{R}$.

(4) Establish the weighted normalised fuzzy decision matrix.

On the basis of relative weights of criteria (W_{C_i}), the weighted normalised fuzzy decision matrix can be obtained as follows:

$$\tilde{V} = \left[\tilde{v}_{ji}\right]_{m \times n}, \text{ where, } \tilde{v}_{ji} = \tilde{r}_{ji} \times W_{C_i} \tag{15}$$

(5) Determine the FPIRP and FNIRP.

The FPIRP (A^+) and FNIRP (A^-) of RCOs can be determined as follows [43]:

$$A^+ = (\tilde{v}_1^+, \tilde{v}_2^+, \ldots, \tilde{v}_n^+), \tag{16}$$

Where $\tilde{v}_i^+ = \left(\max_j (v_{ji1}), \max_j (v_{ji2}), \max_j (v_{ji3}) \right)$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-) \tag{17}$$

Where $\tilde{v}_i^- = \left(\min_j (v_{ji1}), \min_j (v_{ji2}), \min_j (v_{ji3}) \right)$

For $j = 1, 2, \ldots, m$ and $i = 1, 2, \ldots, n$

(6) Calculate the distance from each RCO to FPIRP and FNIRP respectively.

The distance of two triangular fuzzy numbers can be computed as follows [43]:

$$d_j^+ = \sum_{i=1}^{n} d(v_{ji}, v_i^+) = \sum_{i=1}^{n} \sqrt{\frac{1}{3}\left[\left(g_{ji} - g_i^+\right)^2 + \left(h_{ji} - h_i^+\right)^2 + \left(p_{ji} - p_i^+\right)^2\right]} \tag{18}$$

$$d_j^- = \sum_{i=1}^{n} d(v_{ji}, v_i^-) = \sum_{i=1}^{n} \sqrt{\frac{1}{3}\left[\left(g_{ji} - g_i^-\right)^2 + \left(h_{ji} - h_i^-\right)^2 + \left(p_{ji} - p_i^-\right)^2\right]} \tag{19}$$

(7) Calculate the closeness coefficient of each RCO.

$$CC_j = \frac{d_j^-}{d_j^+ + d_j^-} \quad \left(j = 1, 2, \ldots, m\right) \tag{20}$$

(8) Rank the RCOs.

The value of CC_j belongs to the interval [0, 1]. When the distance of a RCO to FPIRP is 0 ($d_j^+ = 0$), CC_j is equal to 1; whereas when the distance of an RCO to FNIRP is 0 ($d_j^- = 0$), CC_j will be 0. Therefore, a higher value of CC_j represents a better RCO. The best alternative is the one with largest CC_j value, which shows the greatest relative closeness to the ideal solution.

However, it should be noted that the notion of CC_j may lead to inconsistency in some occasions, and thus a new aggregation function has been proposed to overcome this problem. The model proposed by Zimmermann and Zysno [52] is applied. According to this model, the membership functions of the fuzzy set of alternatives closest to the ideal point and that farthest to the anti-ideal point are calculated as Eq. (21) and Eq. (22).

$$u^+ = \frac{1}{d^+ + 1} \tag{21}$$

$$u^- = 1 - \frac{1}{d^- + 1} = \frac{d^-}{d^- + 1} \tag{22}$$

And, another rating of each alternative is then calculated according to its membership degree to the intersection of the two fuzzy sets according to the fuzzy set intersection model proposed by Yager [53], shown as below.

$$CC_j^* = u^{+\cap-} = 1 - \min[1,\ (1\text{-}\ u^+)^p + (1 - u^-)^p]^{1/p} \ for\ p \geq 1. \tag{23}$$

Where, P is a measure of how strongly the simultaneous satisfaction of the two conditions that the most preferable alternative should have “the shortest distance from the ideal solution” and “the farthest distance from the negative ideal solution” [54]. According to definitions of fuzzy intersections, the following properties can be concluded for the calculation using Eq. (23).

1) if $P \rightarrow \infty$, then $u^{+\cap -} = \min(u^{+}, u^{-})$ (Zadeh connective)

2) if $P = 1$, then $u^{+\cap -} = \max[0, (u^{+} + u^{-} - 1)]$ (Lukasiewicz connective)

4. A case study of proposed methods in the RCOs selection problem of waterway congestion

In this section, a case study of the Yangtze River is conducted to illustrate the fuzzy TOPSIS methods, and the evaluation results are then compared with those obtained from other MCDM methods (i.e. VIKOR, ELECTRE and PROMETHEE). In this paper, waterway congestion refers to a generic term including various activities and behaviours that affect the normal navigation of vessels.

4.1 Modelling of cost benefit analysis

Based on the research results of a preliminary study conducted by Zhang et al., [7], single assessment index is selected as the cost criterion for the evaluation of alternatives (RCOs), that is, the total cost (C_1) of RCOs which composes of the cost for infrastructure construction, maintenance service and possible economic loss. While four benefit criteria are selected and described as follows:

- C_2: Effect of enhancing the safety level of large-tonnage ships;
- C_3: Effect of guaranteeing the navigable dimensions and safety management during dry seasons;
- C_4: Effect of reducing the grounding accidents;
- C_5: Effect of strengthening safety management of private owner ships.

Besides, several RCOs are put forward in combination with the current development of the Yangtze River, suggestions are received from domain experts and some government regulations [45].

- RCO1: Channel dredging and maintenance
- RCO2: Prohibition of navigation
- RCO3: Real-time channel dimension monitoring
- RCO4: On-site supervision
- RCO5: Loading restriction
- RCO6: Crew management and training

After obtaining the criteria and RCOs, the model of cost-benefit analysis can be established, as shown in Fig. 3.

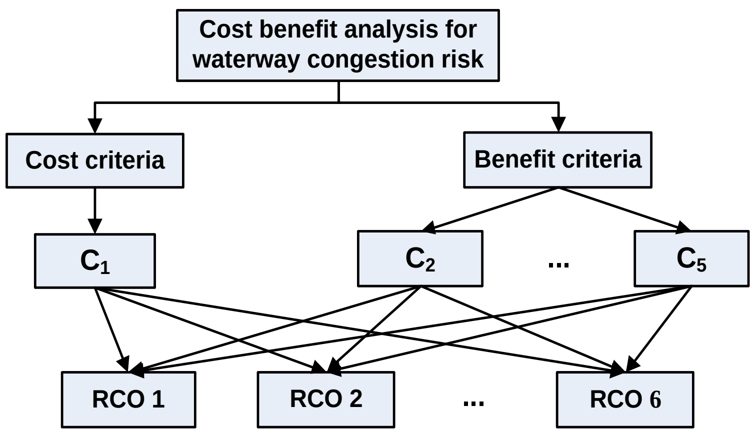

Fig. 3. Model of cost-benefit analysis for waterway congestion in the Yangtze River

4.2 Calculation of the criteria weights under certain CBR

In this research, the initial CBR is set as 1:1, which means an equal importance of cost and benefits to decision makers when dealing with the waterway congestion problems. The relative weights of cost and benefits can be calculated using Eq. (1) and (2). So, $C = B = 0.5$. Importance of each criterion within cost and benefit groups are then calculated by using AHP method according to experts' judgements, shown as Table 1. The judgements come from three domain experts. They include [7]:

- Expert No.1: An experienced master with more than 5 years of experience (as a master) on the operation of board ships in the Yangtze River.
- Expert No.2: A professor engaged in maritime research for more than 15 years with particular reference to the ship operations in the Yangtze River.
- Expert No.3: A senior officer in-charge of safety regulation of the Yangtze River from China Maritime Safety Administration (China MSA).

Table 1 Weight of criteria [7]

Group	Initial weight	Criteria	Local weight	Global weight
Cost criteria	0.5	C1 Total cost	1	0.5
Benefit criteria	0.5	C_2 Effect of enhancing the safety level of large-tonnage ships	0.234	0.117
		C_3 Effect of guaranteeing the navigable dimensions and safety management during dry season	0.221	0.110
		C_4 Effect of reducing the grounding accidents	0.332	0.166
		C_5 Effect of strengthening safety management of self-employed ships	0.213	0.107

4.3 Establishment of the fuzzy sets and evaluation of the RCOs

The performance of six RCOs are evaluated by the experts in terms of the five criteria, and they share the same weigh when aggregating their judgements. The original results are shown in Table 2.

Table 2 Quantitative evaluation of RCOs in terms of different criteria

	C_1	C_2	C_3	C_4	C_5
RCO1	1.0 H	0.67 ME, 0.33 E	0.67 E, 0.33 GE	1.0 E	0.5 LE, 0.5 SE
RCO2	1.0 VH	0.5 ME, 0.5 E	0.5 E, 0.5 GE	0.67 E, 0.33 GE	0.5 SE, 0.5 ME
RCO3	1.0 M	0.33 SE, 0.67 ME	0.67 ME, 0.33 E	0.5 ME, 0.5 E	1.0 SE
RCO4	0.67 M, 0.33 L	1.0 ME	1.0 ME	0.33 SE, 0.67 ME	0.67 ME, 0.33 E
RCO5	0.5 M, 0.5 L	0.5 SE, 0.5 ME	0.33 SE, 0.67 ME	1.0 ME	1.0 ME
RCO6	1.0 L	0.33 SE, 0.67 ME	1.0 SE	0.67 SE, 0.33 ME	0.5 SE, 0.5 ME

The rating of RCO1 in terms of criterion C_1 is "1.0 H", which represents a 100% brief degree belonging to the rate of "High". It indicates that all the experts agree on the idea that the cost of implementing RCO1 is "High". The interpretation of these linguistic variables and how they are transferred into fuzzy numbers are presented as follows.

Linguistic variables for cost criteria rating are categorised as "Very High" (VH), "High" (H), "Moderate" (M), "Low" (L) and "Very Low" (VL). The TFN of each rating is obtained through a survey of the experts. The TFNs are generated via weighted average of expert's evaluation ratings which are determined within an interval from 0 (worst) to 10 (best). The expert's judgement hold the same weight in terms of their knowledge and working experience when aggregating their judgements. Taking H as an example, the collected data from experts are (0.5, 2.5, 4.5), (1, 3, 5) and (1.5, 3.5, 5.5) respectively, thus the TFN for H can be calculated as follows:

$$(\frac{0.5+2.5+4.5}{3},\frac{1+3+5}{3},\frac{1.5+3.5+5.5}{3})=(1,3,5)$$

TFNs for cost criteria are shown in Table 3.

Table 3 TFNs for cost criteria

Evaluation scale of cost criteria	TFNs
Very High (VH)	(0, 0, 3)
High (H)	(1, 3, 5)
Moderate (M)	(3, 5, 7)
Low (L)	(5, 7, 9)
Very Low (VL)	(7, 10 ,10)

Linguistic variables for benefits criteria are also rated at 5 levels "Greatly Effective" (GE), "Effective" (E), "Moderately Effective" (ME), "Slightly Effective" (SE) and "Least Effective" (LE). The fuzzy set and TFNs of the four benefit criteria are defined in Table 4 using a similar way.

Table 4 TFN of each rating in benefits criteria

Evaluation scale of cost criteria	TFNs
Least Effective (LE)	(0, 0, 3)
Slightly Effective (SE)	(1, 3, 5)
Moderately Effective (ME)	(3, 5, 7)
Effective (E)	(5, 7, 9)
Greatly Effective (GE)	(7, 10 ,10)

Based on the fuzzy sets established in this section, the experts' judgments in Table 2 can be converted into fuzzy numbers using Eq. (11), as shown in Table 5. Considering the evaluation results of RCO1 as an example, rating "1.0 H" can be converted according to its corresponding TFN (1, 3, 5) as follows:

$$r_{11}=(1,3,5)\times 1.0=(1.00,\ 3.00,\ 5.00)$$

Table 5 TFNs of the evaluation results

	C_1	C_2	C_3	C_4	C_5
RCO1	(1.00, 3.00, 5.00)	(3.66, 5.66, 7.66)	(5.66, 7.99, 9.33)	(5.00, 7.00, 9.00)	(0.50, 1.50, 4.00)
RCO2	(0.00, 0.00, 3.00)	(4.00, 6.00, 8.00)	(6.00, 8.50, 9.50)	(5.66, 7.99, 9.33)	(2.00, 4.00, 6.00)
RCO3	(3.00, 5.00, 7.00)	(2.34, 4.34, 6.34)	(3.66, 5.66, 7.66)	(4.00, 6.00, 8.00)	(1.00, 3.00, 5.00)
RCO4	(3.66, 5.66, 7.66)	(3.00, 5.00, 7.00)	(3.00, 5.00, 7.00)	(2.34, 4.34, 6.34)	(3.66, 5.66, 7.66)
RCO5	(4.00, 6.00, 8.00)	(2.00, 4.00, 6.00)	(2.34, 4.34, 6.34)	(3.00, 5.00, 7.00)	(3.00, 5.00, 7.00)
RCO6	(5.00, 7.00, 9.00)	(2.34, 4.34, 6.34)	(1.00, 3.00, 5.00)	(1.66, 3.66, 5.66)	(2.00, 4.00, 6.00)

The TFNs are normalised using Eq. (14). For instance, the normalisation of RCO1 in terms of C_1 can be achieved as follows:

$$\tilde{r}_{11} = \frac{r_{11}}{p_1^+} = \left(\frac{1.00}{9.00}, \frac{3.00}{9.00}, \frac{5.00}{9.00}\right) = (0.111,\ 0.333,\ 0.556)$$

Where, p_1^+ denotes the maximum value of upper limit of TFNs under criterion C_1, which should be 9.00 according to the values in the first column of Table 5.

Therefore, the normalised TFNs are shown as Table 6.

Table 6 Normalised TFNs of the evaluation results

	C_1	C_2	C_3	C_4	C_5
RCO1	(0.111, 0.333, 0.556)	(0.458, 0.708, 0.958)	(0.596, 0.841, 0.982)	(0.536, 0.750, 0.965)	(0.065, 0.196, 0.522)
RCO2	(0.000, 0.000, 0.333	(0.500, 0.750, 1.000)	(0.632, 0.894, 1.000)	(0.607, 0.856, 1.000)	(0.261, 0.522, 0.783)
RCO3	(0.333, 0.556, 0.778)	(0.293, 0.543, 0.793)	(0.385, 0.596, 0.806)	(0.429, 0.643, 0.857)	(0.131, 0.392, 0.653)
RCO4	(0.407, 0.629, 0.851)	(0.375, 0.625, 0.875)	(0.316, 0.526, 0.737)	(0.251, 0.465, 0.680)	(0.478, 0.739, 1.000)
RCO5	(0.444, 0.667, 0.889)	(0.250, 0.500, 0.750)	(0.246, 0.457, 0.667)	(0.322, 0.536, 0.750)	(0.392, 0.653, 0.914)
RCO6	(0.556, 0.778, 1.000)	(0.293, 0.543, 0.793)	(0.105, 0.316, 0.526)	(0.178, 0.392, 0.607)	(0.261, 0.522, 0.783)

Then, according to the weights of criteria obtained in Section 4.2, the weighted normalised TFNs can be calculated using Eq. (15), as shown in Table 7. For instance, the weighted normalised TFN of RCO1 in terms of criterion C_1 can be calculated as follows:

$$v_{11} = \tilde{r}_{11} \times W_{C_1} = (0.111,\ 0.333,\ 0.556) \times 0.5 = (0.056,\ 0.167,\ 0.278)$$

Table 7 Weighted normalised TFNs of the evaluation results

	C_1	C_2	C_3	C_4	C_5
RCO1	(0.056, 0.167, 0.278)	(0.053, 0.083, 0.112)	(0.066, 0.093, 0.109)	(0.089, 0.124, 0.160)	(0.007, 0.021, 0.056)
RCO2	(0.000, 0.000, 0.167)	(0.058, 0.088, 0.117)	(0.070, 0.099, 0.111)	(0.101, 0.142, 0.166)	(0.028, 0.056, 0.084)
RCO3	(0.167, 0.278, 0.389)	(0.034, 0.063, 0.093)	(0.043, 0.066, 0.089)	(0.071, 0.107, 0.142)	(0.014, 0.042, 0.070)
RCO4	(0.203, 0.314, 0.426)	(0.044, 0.073, 0.102)	(0.035, 0.058, 0.081)	(0.042, 0.077, 0.113)	(0.051, 0.079, 0.107)
RCO5	(0.222, 0.333, 0.444)	(0.029, 0.058, 0.088)	(0.027, 0.051, 0.074)	(0.053, 0.089, 0.124)	(0.042, 0.070, 0.098)
RCO6	(0.278, 0.389, 0.500)	(0.034, 0.063, 0.093)	(0.012, 0.035, 0.058)	(0.029, 0.065, 0.101)	(0.028, 0.056, 0.084)

4.4 Ranking of the RCOs

In TOPSIS, the positive and negative ideal solutions are usually the best and the worst solutions in each column, from which the distance of each alternatives to them can be calculated. In this paper, general reference points are employed as the best and worst for all the criteria. Referring to the fuzzy sets, the best solution should be (7, 10, 10), which is normalized as (0.7, 1, 1). Hence, the FPIRP (A^+) and FNIRP (A^-) can be defined as follows:

$$A^+ = \left[(0.7,1,1),(0.7,1,1),(0.7,1,1),(0.7,1,1),(0.7,1,1)\right]$$

$$A^- = \left[(0,0,0.3),(0,0,0.3),(0,0,0.3),(0,0,0.3),(0,0,0.3)\right]$$

The distance from each RCO to FPIRP and FNIRP can be calculated using Eq. (18) and Eq. (19). Taking RCO1 as an example, its distances to FPIRP and FNIRP are calculated as follows:

$$d_1^+ = \sqrt{\frac{1}{3}\left[(0.056-0.7)^2+(0.167-1)^2+(0.278-1)^2\right]} + \sqrt{\frac{1}{3}\left[(0.053-0.7)^2+(0.083-1)^2+(0.112-1)^2\right]} + \sqrt{\frac{1}{3}\left[(0.066-0.7)^2+(0.089-1)^2+(0.109-1)^2\right]} + \sqrt{\frac{1}{3}\left[(0.089-0.7)^2+(0.124-1)^2+(0.160-1)^2\right]} + \sqrt{\frac{1}{3}\left[(0.007-0.7)^2+(0.028-1)^2+(0.056-1)^2\right]} = 4.0499$$

$$d_1^- = \sqrt{\frac{1}{3}\left[(0.056-0)^2+(0.167-0)^2+(0.278-0.3)^2\right]} + \sqrt{\frac{1}{3}\left[(0.053-0)^2+(0.083-0)^2+(0.112-0.3)^2\right]} + \sqrt{\frac{1}{3}\left[(0.066-0)^2+(0.089-0)^2+(0.109-0.3)^2\right]} + \sqrt{\frac{1}{3}\left[(0.089-0)^2+(0.124-0)^2+(0.160-0.3)^2\right]} + \sqrt{\frac{1}{3}\left[(0.007-0)^2+(0.028-0)^2+(0.056-0.3)^2\right]} = 0.6147$$

Similarly, distances of all RCO to FPIRP and FNIRP can be computed, which are presented in Table 8.

Table 8 Distances of each RCO to FPIRP and FNIRP

Risk control options (RCOs)	Distance to FPIRP (d^+)	Distance to FNIRP (d^-)
RCO1	4.0499	0.6147
RCO2	4.1170	0.5856
RCO3	3.9847	0.7033
RCO4	3.9389	0.7279
RCO5	3.9397	0.7525
RCO6	3.9326	0.8194

Finally, the closeness coefficient of RCOs can be calculated using Eq. (20). For instance the closeness coefficiency of RCI is obtained as follows.

$$CC_1 = \frac{d_1^-}{d_1^+ + d_1^-} = \frac{4.0499}{4.0499 + 0.6147} = 0.1318$$

Similarly, the closeness coefficients and rankings of six RCOs can be obtained and are shown in Table 9.

Table 9 Ranking of RCOs in terms of closeness coefficient

RCOs		CC	Ranking
RCO1	Channel dredging and maintenance	0.1318	5
RCO2	Prohibition of navigation	0.1245	6
RCO3	Real-time channel dimension monitoring	0.1500	4
RCO4	On-site supervision	0.1559	3
RCO5	Loading restriction	0.1603	2
RCO6	Crew management and training	0.1724	1

It can be seen from Table 9 that when taking the equal importance of cost and benefits, RCO6 (Crew management and training) ranks the first, followed by RCO5 (Loading restriction) and RCO4 (On-site supervision), while RCO2 (Prohibition of navigation) is the least cost-effective one with the lowest value of CC.

As a complementary, the corresponding membership in the fuzzy set of alternatives that have the shortest distance from the ideal solution and in those have the farthest distance from the negative ideal solution are also calculated based on the distance in Table 8 using Eq. (21) and (22). The results are shown in Table 10.

Table 10 Distance measurement and membership values

	d^+	d^-	u^+	u^-
RCO1	4.0499	0.6147	0.1980	0.3807
RCO2	4.1170	0.5856	0.1954	0.3693
RCO3	3.9847	0.7033	0.2006	0.4129
RCO4	3.9389	0.7279	0.2025	0.4213
RCO5	3.9397	0.7525	0.2024	0.4294
RCO6	3.9326	0.8194	0.2027	0.4504

Then, the total rating and ranking of each RCO is calculated using Eq. (23), and results are shown in Table 11.

Table 11 Total ratings and ranking of RCOs

	$P=1$	$P=2$	$P=3$	$P=\infty$
CC_1^*	0 (1)	0 (5)	0.0901 (5)	0.1980 (5)
CC_2^*	0 (1)	0 (5)	0.0828 (6)	0.1954 (6)
CC_3^*	0 (1)	0.0082 (4)	0.1066 (4)	0.2006 (4)
CC_4^*	0 (1)	0.0146 (3)	0.1116 (3)	0.2025 (2)

CC_5^*	0 (1)	0.0193 (2)	0.1150 (2)	0.2024 (3)
CC_6^*	0 (1)	0.0316 (1)	0.1237 (1)	0.2027 (1)

It can be seen from Table 11 that different ratings are yielded with respect to different behavioural patterns (represented by different P instance) of decision makers. For example, the ranking of RCO4 and RCO5 is reversed in the instance with P=3 and $P=\infty$, respectively. In some cases, the preference of RCOs cannot be distinguished clearly due to the same ratings (e.g. when P =1). Thus in section 5, the RCOs under different congestion risk states are ranked based on the results obtained using Eq. (20).

4.5 Comparative analysis of the results using different MCDM methods

Based on the original decision matrix from Table 1, VIKOR, ELECTRE and PROMETHEE (type I and II) are applied in the same case study for the decision of finding the most cost effective solution to the waterway congestion problem. It allows for a more practical and effective investigation of the applicability of different MCDM methods through comparative analysis. In this subsection, we mainly focus on the comparison of their pros and cons in the real-life applications, as well as the difference of results obtained from them. Thus, detailed information on how to conduct these MCDM methods step by step is not introduced here, which can be found in [46], [47], and [48] for further reference. It should be noted that the linguistic judgements in the Table 2 need to be converted into crisp values before further calculation. Among these criteria, only C_1 is a non-beneficial attribute, while the rest are beneficial ones. The evaluation results obtained using VIKOR, ELECTRE, and PROMETHEE method are shown in Table 12, Table 13, and Table 14 respectively.

Table 12 S_i, R_i and Q_i values (v=0.5) for each RCO

	S_i	R_i	Q_i
RCO 1	0.6620	0.3783	0.6706
RCO 2	0.7083	0.4594	1.0000
RCO 3	0.6101	0.2972	0.3213
RCO 4	0.5734	0.2705	0.1368
RCO 5	0.5732	0.2567	0.1091
RCO 6	0.5661	0.2161	0.0000

VIKOR method ranks the alternatives according to the values of three scalar quantities, that are, S_i, R_i, and Q_i, where S_i and R_i denote the utility measures and regret measure for each alternative, while Q_i is a consideration of both [46]. For the case study, the best alternative is the one with the smallest Q_i value, only if the "acceptable advantage" and "acceptable stability in decision making" are satisfied simultaneously. According to the Q_i value in Table 12, the following ranking is obtained: RCO6 > RCO5 > RCO4 > RCO3 > RCO1 > RCO2, with an assumption that v is 0.5. However, it results Q(RCO5) - Q(RCO6) = 0.1091 less than DQ = 1/(6-1) = 0.2, which does not satisfy the "acceptable advantage". This means that RCO4, RCO5, and RCO6 are judged to be too much close to distinguish the best one among them. Consequently, a subset of preferable options can be defined, and the final result indicates the subset RCO6, RCO5, and RCO4 as a group of compromise solution.

Table 13 Concordance and discordance indexes, and threshold values

C (p, q)	c_{pq}	*if* $c_{pq} \geq \underline{c}$	D (p, q)	d_{pq}	*if* $d_{pq} \leq \underline{d}$	$A_p \rightarrow A_q$
C12	0.50	NO	D12	0.50	NO	-

C13	0.39	NO	D13	0.61	NO	-
C14	0.39	NO	D14	0.61	NO	-
C15	0.39	NO	D15	0.61	NO	-
C16	0.39	NO	D16	0.61	NO	-
C21	0.50	NO	D21	0.50	NO	-
C23	0.50	NO	D23	0.50	NO	-
C24	0.39	NO	D24	0.61	NO	-
C25	0.39	NO	D25	0.61	NO	-
C26	0.50	NO	D26	0.50	NO	-
C31	0.61	YES	D31	0.39	YES	3→1
C32	0.50	NO	D32	0.50	NO	-
C34	0.28	NO	D34	0.72	NO	-
C35	0.39	NO	D35	0.61	NO	-
C36	0.39	NO	D36	0.61	NO	-
C41	0.61	YES	D41	0.39	YES	4→1
C42	0.61	YES	D42	0.39	YES	4→2
C43	0.72	YES	D43	0.28	YES	4→3
C45	0.33	NO	D45	0.67	NO	-
C46	0.50	NO	D46	0.50	NO	-
C51	0.61	YES	D51	0.39	YES	5→1
C52	0.61	YES	D52	0.39	YES	5→2
C53	0.61	YES	D53	0.39	YES	5→3
C54	0.67	YES	D54	0.33	YES	5→4
C56	0.38	NO	D56	0.62	NO	-
C61	0.61	YES	D61	0.39	YES	6→1
C62	0.61	YES	D62	0.39	YES	6→2
C63	0.72	YES	D63	0.28	YES	6→3
C64	0.50	NO	D64	0.50	NO	-
C65	0.62	YES	D65	0.38	YES	6→5
$\underline{c}$ = 0.51; $\underline{d}$ = 0.49						

The key to the ELECTRE method lays on the construction of the outranking relations between alternatives - comparing each pair of actions each time. In this method, considering two alternatives A_p and A_q, a concordance set C (p, q) is developed containing all the criteria, for which alternative A_p performs better than A_q, or at least indifference to it [49]. Conversely, D (p, q) composes the remaining criteria. The concordance index c_{pq} between alternatives A_p and A_q is then calculated, which represents how much A_p is to be preferred to A_q. Also, two threshold values $\underline{c}$ and $\underline{d}$ which are usually set by decision makers are needed to determine whether the outranking relation $A_p \rightarrow A_q$ is true or not. This relation is defined true only if the results satisfy $c_{pq} \geq \underline{c}$ and $d_{pq} \leq \underline{d}$ at the same time. All the information needed for decision making in this case-study is summarized in Table 13, and based on that, an outranking graph can be depicted, showing that the RCO 6 is stated to be the best alternative among others.

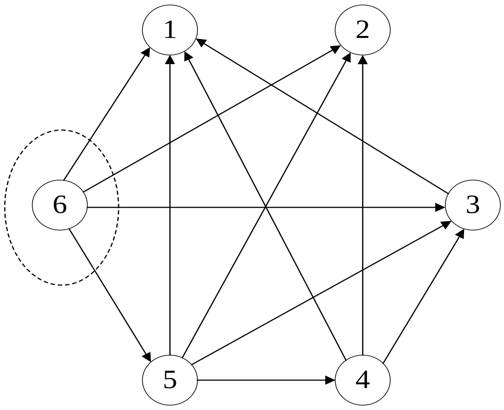

Fig. 6. Outranking graph

Table 14 Values of π (a_1, a_2), and positive and negative outgoing flow

π	RCO 1	RCO 2	RCO 3	RCO 4	RCO 5	RCO 6	Φ^+
RCO 1	-	0.5000	0.3930	0.3930	0.3930	0.3930	0.4144
RCO 2	0.4170	-	0.5000	0.3340	0.3930	0.3930	0.4074
RCO 3	0.6170	0.4700	-	0.2760	0.4170	0.3340	0.4228
RCO 4	0.6170	0.5722	0.7240	-	0.3340	0.6070	0.5708
RCO 5	0.6070	0.6670	0.6070	0.6660	-	0.3930	0.5880
RCO 6	0.6170	0.6170	0.6070	0.5000	0.6170	-	0.5916
Φ^-	0.5750	0.5652	0.5662	0.4338	0.4308	0.4240	

The PROMETHEE method is another outranking based MCDM method, in which the type I provides the partial ordering of the alternatives, whereas, type II can achieve a full ranking. In this method, a preference function has to be decided to each criterion. Generally, there are six types of preference functions [49], and some of them require the definition of one or two preferential parameters, which may be difficult for the decision makers in real time applications. Thus, in this study, the decisions are made based on usual-criteria preference functions with no thresholds to minimize the problem of rank reversals. The preference index π (A_p, A_q), and positive and the negative outranking flows are calculated and shown as Table 12. For a complete ranking in PROMETHEE II method, net flow values are calculated for each alternatives ($\Phi = \Phi^+ - \Phi^-$), revealing the following ranking: RCO6 > RCO5 > RCO4 > RCO3 > RCO2 > RCO1.

Based on the above results, the applicability of all examined MCDM methods to the waterway congestion management problems are compared in the Table 15.

Table 15 Applicability of the examined MCDM methods to waterway congestion management problems

MCDM methods	Results of decision	Applicability
TOPSIS	RCO6 > RCO5 > RCO4 > RCO3 > RCO1 > RCO2	YES
VIKOR	RCO6, RCO5, and RCO4 to be preferred	YES

ELECTRE	RCO6 to be preferred	YES
PROMETHEE I	Partial ranking. RCO6 to be preferred	YES
PROMETHEE II	RCO6 > RCO5 > RCO4 > RCO3 > RCO2 > RCO1	YES

5 Evaluation of RCOs under dynamic congestion risk states

When choosing appropriate RCOs for dealing with waterway congestions, the importance of cost and benefits considered by decision makers depends mostly on the current status of the risk. Thus the relative importance of cost often varies with the changing risk levels, which can be represented by different values of CBR. The congestion risk early-warning for the Yangtze River is classified into four levels, and interviews on domain experts indicated that the CBR used here can well reflect the situation of different early-warning levels. Thus, in this section, the rankings of RCOs under fluctuated risk levels are evaluated by setting various values of CBR in different scenarios.

The initial value of CBR in the case study is set as 1:1, which indicates the same preference to both cost and benefits when making decisions. Taking the initial CBR (1:1) as a critical condition, other scenarios are described as follows:

Table 16 CBR of different scenarios (SCEN)

SCEN 1	SCEN 2	SCEN 3	SCEN 4	SCEN 5	SCEN 6	SCEN 7	SCEN 8	SCEN 9
5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5

It is clear that the congestion risk gradually increases from SCEN 1 to SCEN 9, with the value of CBR declines from 5:1 to 1:5, which shows a promotion of the importance of benefit along with the increasing of congestion risk.

Through the similar calculation procedure described from Section 4.2 to Section 4.4, the weights of criteria in different scenarios can be obtained and shown in Table 17, while the closeness coefficients of criteria in different scenarios are shown in Table 18.

Table 17 Weights of criteria in different scenarios

Criteria	SCEN 1	SCEN 2	SCEN 3	SCEN 4	SCEN 5	SCEN 6	SCEN 7	SCEN 8	SCEN 9
C_1	0.833	0.800	0.750	0.667	0.500	0.333	0.250	0.200	0.167
C_2	0.039	0.047	0.059	0.078	0.117	0.156	0.175	0.187	0.195
C_3	0.037	0.044	0.055	0.074	0.110	0.148	0.166	0.177	0.184
C_4	0.055	0.066	0.083	0.110	0.166	0.221	0.249	0.265	0.276
C_5	0.036	0.043	0.053	0.071	0.107	0.142	0.160	0.171	0.178

Table 18 Closeness coefficients of RCOs in different scenarios *

RCOs	SCEN 1	SCEN 2	SCEN 3	SCEN 4	SCEN 5	SCEN 6	SCEN 7	SCEN 8	SCEN 9
RCO 1	0.1627	0.1588	0.1532	0.1445	0.1318	0.1295	0.1332	0.1366	0.1394
RCO 2	0.1253	0.1244	0.1233	0.1224	0.1245	0.1328	0.1392	0.1437	0.1469
RCO 3	0.1990	0.1938	0.1862	0.1736	0.1500	0.1319	0.1275	0.1271	0.1278
RCO 4	0.2108	0.2052	0.1968	0.1829	0.1560	0.1334	0.1264	0.1246	0.1247
RCO 5	0.2173	0.2115	0.2029	0.1885	0.1604	0.1360	0.1276	0.1250	0.1245
RCO 6	0.2360	0.2298	0.2203	0.2044	0.1724	0.1424	0.1300	0.1247	0.1225

* Rankings are according to the accurate number while only 4 significant digits are kept in the table.

Based on the results in Table 18, the variation trends of closeness coefficient of RCOs in different scenarios can be mapped as shown in Fig. 7.

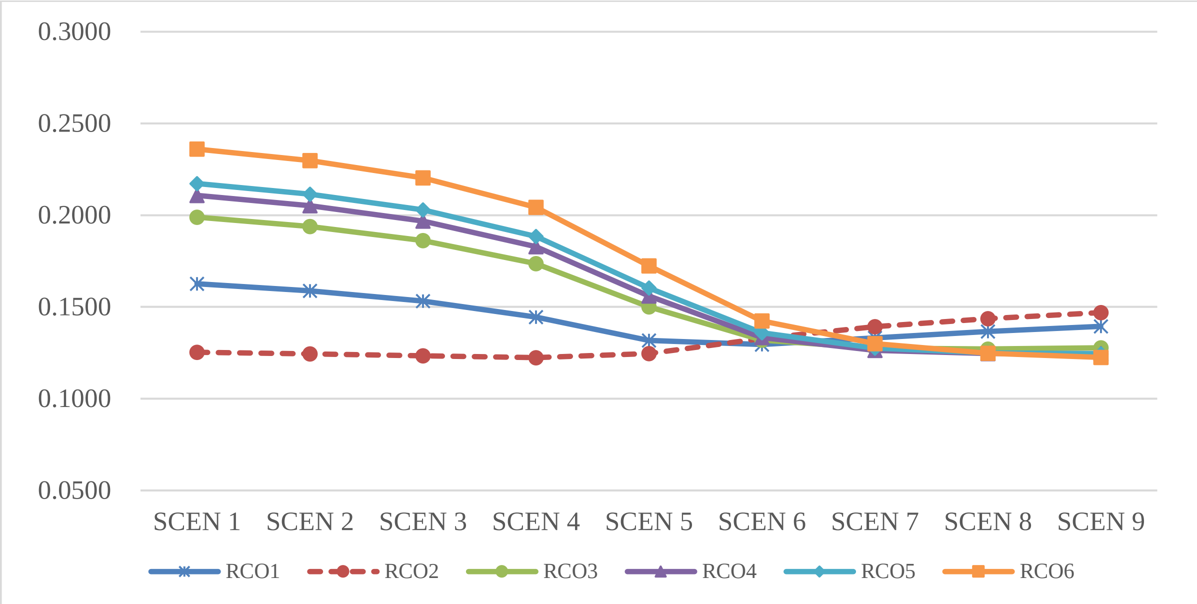

Fig. 7. Variation of closeness coefficients of RCOs in different scenarios

It can be seen from the above picture that as the congestion risk increases (from SCEN 1 to SCEN 9), the closeness coefficients from RCO3 to RCO6 show a continuous downward trend, while that of RCO1 and RCO2 decrease slightly at first, but then they climb up again and exceed other RCOs with the increase of risk.

For more intuitive expression of the cost effectiveness of the RCOs in different scenarios, these RCOs are ranked according to their closeness coefficients. The evaluation results are concluded in Table 19 and further illustrated in Fig. 8.

Table 19 Rankings of RCOs in different scenarios

RCOs	SCEN 1	SCEN 2	SCEN 3	SCEN 4	SCEN 5	SCEN 6	SCEN 7	SCEN 8	SCEN 9
RCO 1	5	5	5	5	5	6	2	2	2
RCO 2	6	6	6	6	6	4	1	1	1
RCO 3	4	4	4	4	4	5	5	3	3
RCO 4	3	3	3	3	3	3	6	6	4
RCO 5	2	2	2	2	2	2	4	4	5
RCO 6	1	1	1	1	1	1	3	5	6

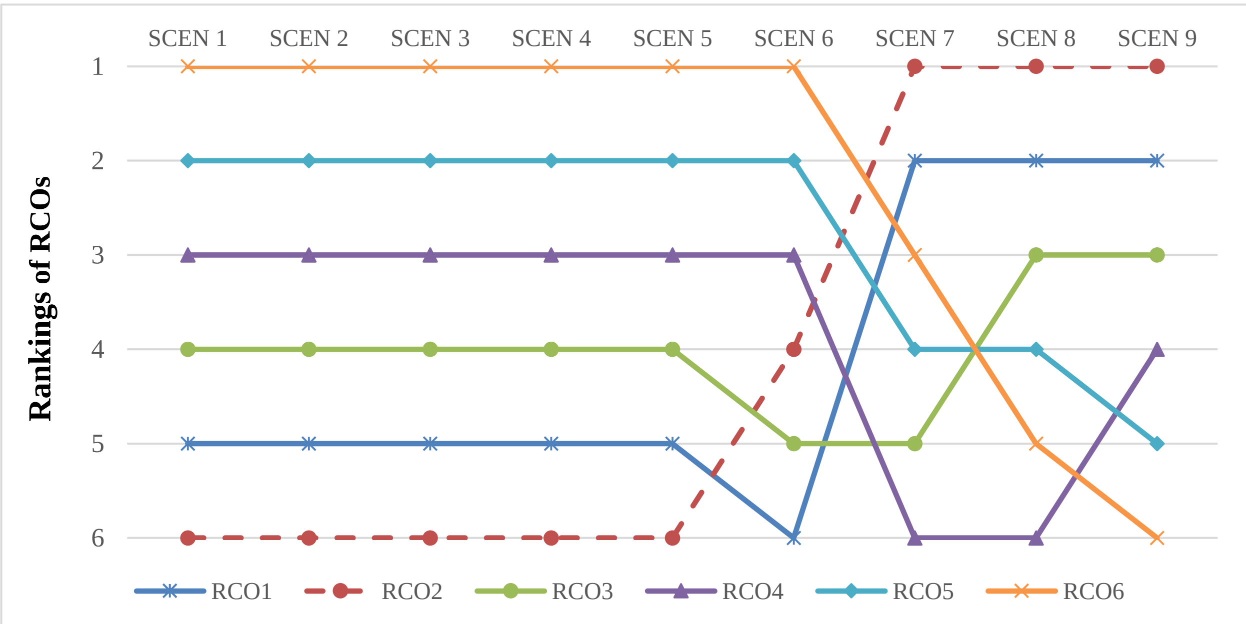

Fig. 8. Variation of rankings of RCOs in different scenarios

Although minor fluctuations exist, the changing trends of the curves in Fig. 8 are basically in line with that of Fig. 7. As the congestion risk increases, rankings of RCO1 and RCO2 improve significantly while the ranking of RCO5 and RCO6 declines after the SCEN 6, which to some extent testifies the rationality and logicality of the proposed model.

6. Discussion

Further discussions on these RCOs and their changes of the preference under different congestion risk conditions are provided as below.

- RCO1: Channel dredging and maintenance

Channel dredging generally refers to removing sediment in the waterway through the use of dredgers or other equipment, which is the primary way to increase or maintain the dimension of channels. Based on the purpose, it can be divided into two categories, namely, construction-oriented dredging and maintenance-oriented dredging. Although channel dredging and maintenance has a positive effect on reducing the waterway congestion risks, the high cost involved usually hinder its application in practice, calling for a cost-benefit analysis before its final implementation. Besides, its potential impact on environment degradation should not be ignored. The quality of water, soil and air near the channel areas under construction will all be affected seriously, due to its own characteristics of channel dredging-related projects.

It can be seen from the Fig. 8 that the ranking of RCO1 remains at 5th and 6th from SCEN 1 to SCEN 6, but rises dramatically to 2nd place in the SCEN 7 and remains the same position until the end. Therefore, the RCO1 is considered to have good cost effectiveness only in the condition of relatively high congestion risk.

- RCO2: Prohibition of navigation

Prohibition of navigation is a kind of man-made intervention procedures conducted by waterway safety authorities through predetermining berthing areas for ships under special circumstances such as harsh navigable environments, navigation-obstruction due to waterway construction. It can be subdivided as one-way prohibition and full prohibition. This option can obviously reduce the waterway congestion risks, but it will inevitably cause huge economic losses at the same time. A careful cost-benefit analysis is also needed so that it can be conducted in right occasions.

RCO2 holds the worst ranking from SCEN 1 to SCEN 5. However, it shows an upward trend from SCEN 5 and jumps to the first place in SCEN 7, which indicates its favourable effects on the risk control regardless of any cost. Thus, it has immense potential to be applied as an emergency countermeasure under high congestion risk conditions.

- RCO3 : Real-time channel dimension monitoring

As the upstream flow of the Yangtze River is affected by both seasons and the Three Gorges Dam, the navigation environment shows a changeable characteristic. Thus, the monitoring and releasing of real-time channel dimension information through network, and marine very high frequency (VHF) radio is of great importance to guarantee the navigational safety and avoid congestion risk, especially during the dry season.

The ranking of RCO3 maintains a relative stable trend in various scenarios. Thus, management authorities are suggested to treat it as a promising complement according to the current risk level of waterway congestions.

- RCO4: On-site supervision

On-site supervision is the supervision carried out by officers from maritime administration though guard boats or helicopters, aiming to investigate violations of ships and maintain a good traffic order. The costs of on-site supervision compose of vehicle maintenance costs and labour costs.

The ranking of RCO4 keeps in the third place from SCEN 1 to SECN 6 with a superior cost effectiveness, which can be used by maritime administration authorities as one of the main countermeasure for waterway congestion risk mitigation.

- RCO5: Loading restriction

RCO5 is developed according to the relevant regulations from the Yangtze River Maritime Affairs Bureau. This RCO can prevent grounding accidents caused by overloading of ships. However, it will increase the operating costs of the ships, and reduce the cargo transport efficiency.

Showing a similar variation trend as that of RCO4, RCO5 shows a well cost effectiveness with a ranking of 2nd place from SCEN 1 to SECN 6, which should also be considered as a regular countermeasure to reduce the probability of waterway congestion. However its cost effectiveness reduces as the congestion risk increases.

- RCO6: Crew management and training

As the majority of the waterway traffic accidents are related to human error, crew management and training will play a crucial role in reducing the congesting risk through the improvement of operation skills and enhancement of safety awareness. This is a long-term countermeasure of fundamental importance, which has been receiving attention from authorities all levels. RCO6 presents an opposite variation trend compared to RCO1 and RCO2. It has the best cost-effectiveness from SCEN 1 to SCEN 6, but its superiority losses gradually as the congestion risk is getting critical. Therefore, RCO6 can be used as a routine countermeasure to reduce the congestion risk even if it has no significant effect when handling the situation of high risks.

In this research, there are two main kinds of criteria which are cost and benefit. The cost contains only one criterion, while the benefit is composed of four criteria which are developed according to the four safety critical factors identified in a previous study [7]. The weight of each criterion is influenced and determined by two factors. Firstly, the relative importance of cost and benefit are decided according the risk attitude of decision makers in different risk conditions, as their attitudes towards risks will affect behaviour associated with risk management activities. Generally, in a relatively high risk condition, decision makers may prefer an RCO with more beneficial outcomes, which means they will try to make every effort to avoid the risk (risk-aversion attitude), resulting in a relatively low CBR. While in the condition of low risk levels, more attention will be paid on reducing the cost of RCOs (risk-seeking attitude), which can be represented with a relatively high CBR. Secondly, the local weight of each criteria within the benefit group is determined using AHP method according to experts' judgements. The final weight of each criterion is then calculated considering both importance of cost/benefit, and their local weight within the cost/benefit. It can be seen from the evaluation results that the observed changes in the preferential ranking order of RCOs are in accordance with the real-life situation. For example, as the increase of congestion risks, the ranking of RCO2 (Prohibition of navigation) shows a continuous rising trend, growing form the last to the first. While, the preferential ranking of RCO6 (Crew management and training) shows an opposite trend, this is due to the fact that it takes long to observe the improvement of crew under well training and management, which is more suitable to be applied as a long-term strategy rather than being used in the case of an emergency.

Waterway congestion prevention and control has become a crucial part in the navigational safety management, and some countermeasures have been enforced as regulations. For instance, it is allowed that in case of an emergency, operating personnel can conduct repairing/dredging work on the damaged channels immediately without any permission from local administrative department [50]. This provision shows a similar idea as the analysis of RCO1. For another example, no-sail ban is always released under high risk situations caused by heavy fog, landslide and torrential rain, which is consistent with the preferential ranking of RCO2. Besides, crew management and training has been considered as an important routine management method in many safety regulations (e.g. [51]) for risk prevention. Thus, the evaluation results presented above are in harmony with the current navigation management regulations to a significant extent, which proves the feasibility and reliability of the proposed method in selection of the RCOs to deal with inland waterway congestions under dynamic risk conditions. Having said so, this paper has a couple of shortcomings as follows, which should be solved in the future research. First, this paper is conducted with emphases on the development and application of risk-based decision making methods, and the ranking of RCOs under various congestion risk conditions, so these RCOs are just investigated as a case study without categorization. This model has the potential to be extended to classify the RCOs according to decision makers' requirements to provide more practicable reference. Second, although rational and sound results have been obtained in this study with the application of CBR in the study of waterway congestion risks, in real life where a large set of hazardous scenarios exist, it is not always easy and straightforward to set specific value for different risk conditions. Besides, the possible close importance between cost and benefit may result the low spread of closeness coefficients when studying the changing trend of RCOs under different risk conditions. Thus, further research is needed to find out more generic factors that are able to distinguish between different risk conditions, especially in other risk-based decision-making scenarios.

7. Conclusion

In this paper, the CBR is introduced to represent different risk status and applied in combination with the fuzzy TOPSIS method to evaluate the RCOs of inland waterway congestions under dynamic risk conditions, in order to choose the most cost-effective one in a dynamic risk environment. These RCOs present a variety of changings on cost effectiveness when different importance of cost and benefit are given, which reflects the preference of decision makers in selecting the suitable RCOs under different risk conditions. The main contribution of this research is threefold. First, not only a series of practical and helpful risk control options (RCOs) to manage the inland waterway congestions are provided, and the final ranking list of alternatives is given, but also the reasons why these alternatives are desirable or undesirable are discussed in details. Such kind of information can be useful for improving the undesirable alternatives and offer useful insights for decision makers and policy makers. Second, this paper takes the influence of risk preferences (attitude) of stakeholders on decision makings into consideration, which enriches the application of fuzzy TOPSIS and enables it to evaluate the effectiveness and preference of RCOs under dynamic congestion risk states. Last, the results from fuzzy TOPSIS is compared with that obtained from other popular MCDM methods such as VIKOR, ELECTRE and PROMETHEE (I and II) in the selection of preferable RCOs of waterway congestions, contributing to the state of the art of MCDM methods, and their applications in inland shipping industry. In addition, the helpful RCOs, as well as the flexible approaches presented in this paper can be tailored and utilized to achieve congestion risk reduction and prevention in other modes of transportation to improve the transportation safety and efficiency. The results of this study also provide useful insights for selecting the rational and cost-effective RCOs in the safety management of shipping industry, which can be further applied in wider risk-based decision-making scenarios.

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