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

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A B S T R A C T

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.

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

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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 disclose 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 sug-