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Effectiveness of maritime safety control in different navigation zones using a spatial sequential DEA model: Yangtze River case

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ABSTRACT

This paper aims to analyze the effectiveness of maritime safety control from the perspective of safety level along the Yangtze River with special considerations for navigational environments. The influencing variables of maritime safety are reviewed, including ship condition, maritime regulatory system, human reliability and navigational environment. Because the former three variables are generally assumed to be of the same level of safety, this paper focuses on studying the impact of navigational environments on the level of safety in different waterways. An improved data envelopment analysis (DEA) model is proposed by treating the navigational environment factors as inputs and ship accident data as outputs. Moreover, because the traditional DEA model cannot provide an overall ranking of different decision making units (DMUs), the spatial sequential frontiers and grey relational analysis are incorporated into the DEA model to facilitate a refined assessment. Based on the empirical study results, the proposed model is able to solve the problem of information missing in the prior models and evaluate the level of safety with a better accuracy. The results of the proposed DEA model are further compared with an evidential reasoning (ER) method, which has been widely used for level of safety evaluations. A sensitivity analysis is also conducted to better understand the relationship between the variation of navigational environments and level of safety. The sensitivity analysis shows that the level of safety varies in terms of traffic flow. It indicates that appropriate traffic control measures should be adopted for different waterways to improve their safety. This paper presents a practical method of conducting maritime level of safety assessments under dynamic navigational environment.

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1. Introduction

Worldwide, maritime safety has captured a great amount of attention in recent decades. For example, studies regarding the Gulf of Finland (Montewka et al., 2014; Mazaheri et al., 2013), Istanbul strait (Aydogdu, 2014), and Yangtze River (Zhang et al., 2013, 2014a) have been conducted. To mitigate the risk and improve the safety of maritime transportation, the International Maritime Organization (IMO), a specialized agency of United Nations whose mission includes improving safety, environmental concerns, maritime security, and efficiency of shipping etc., has approved the guideline for the Formal Safety Assessment (FSA) framework in 2002 (IMO, 2002). The FSA includes five steps that encompass hazard identification, risk assessment, estimated risk management, cost benefit assessments of risk control options and assessments of the options to select. This method has been widely used for risk management in the field of maritime transportation (Wang, 2000; Zhang et al., 2013). Apart from FSA method, continual improvements have been made in maritime regulatory systems, and these regulations have been shown to promote maritime safety, such as the regulations affecting accidents in the Gulf of Finland (Viertola, 2013) and the UK (Bhattacharya, 2012) and shipping in Greece (Tzannatos and Kokotos, 2009).

Among the studies on the safety management for maritime transportation, historical data analyses have been widely used. A majority of the abovementioned papers have used historical accident data for such purposes (Zhang et al., 2013; Tzannatos and

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Kokotos, 2009; Viertola, 2013). Moreover, Ronza et al. (2003) investigated 828 accidents in port areas through event trees constructed to predict the frequency of accidents. Kujala et al. (2009) used theoretical collision models to analyze the maritime safety in the Gulf of Finland based on detailed accident statistics over a ten-year period. Jin and Thunberg (2005) used logic regression models based on accident data from 1981–2000 to analyze fishing vessel accidents in fishing areas of the northeastern United States. By analyzing the accidents from different perspectives, insights have been gained and many effective methods have been adopted for maritime risk management.

The number of maritime accidents and pure economic loss within a period may partly reflect the level of safety. For example, if the number of maritime accidents in one navigation zone is higher than another, it can be assumed that the level of safety is lower than the other zone. In practice, safety index is the most widely used method (Li et al., 2014; Balmat et al., 2009). Li et al. (2014) discovered that the level of safety may vary according to vessel age, size and type, classification sociality, navigation zone, time and season, etc. Specifically, the authors claimed that unique geographical environments would have different impacts on the level of safety in different navigation zones and different seasons. Therefore, different navigation zones with distinguishing navigational environments should be further studied. For each individual ship, navigational safety is tightly related to natural environment, such as current and wind (Balmat et al., 2009). Similarly, Knapp and Van de Velden (2011) have also studied risk related to navigational environment, and their study focused on the effectiveness of maritime safety control based on legislative measures.

Apart from human reliability in relation to safety management (Hänninen and Kujala, 2012; Akhtar and Utne, 2014; Prabhu Gaonkar et al., 2013), a large amount of researches have focused on the influencing variables of maritime safety (Akhtar and Utne, 2014; Viertola, 2013; Akyuz and Celik, 2014; Batalden and Sydnes, 2014; Karahalios, 2014; Bhattacharya, 2012; Hänninen and Kujala, 2014; Yang et al., 2013). Hänninen and Kujala (2012) concluded that the problem of maritime level of safety is complex and should consider the factors of ship condition, navigational environment, maritime regulatory system and human reliability. The influencing variables on maritime safety are summarized and shown in Table 1.

Zhang et al. (2014b) used a generalized Belief Rule Base (BRB) methodology to evaluate the performance of the Maritime Safety Administration(MSA) in the Yangtze River by using search and rescue data. Their research focused on the efficiency of emergency response. For maritime safety control, the five-index safety evaluation method that includes the number of incidents, number of graded accidents, number of casualties, number of shipwrecks and pure economic loss, has been adopted to determine the level of safety in the Yangtze River. Although this method is easy to undertake, it cannot assess the effectiveness of maritime safety measures because it ignores the influence of other safety factors listed in Table 1. In this paper, the authors attempt to assess the effectiveness of safety measures in different navigation zones with full consideration of the influencing variables of navigational environment. The following three basic assumptions are included to make the problem tractable:

(1) The ship condition is suitable for the corresponding navigation zone;
(2) The maritime regulatory system has not changed within the period being studied;
(3) The reliability of the crew in different navigation zones is approximately the same.

For the Yangtze River case, the natural environment can be divided into reservoir area, middle reaches, and lower reaches according to the geographical location (Sun et al., 2013). In this paper, only the waterways in middle reaches are considered where the natural environment can be assumed to be the same. And the differences, including traffic flow, waterway number and range and number of bridges, can be judged by the experienced officers in MSA. Moreover, prior studies have also shown a close relationship between these different factors and maritime safety. The number of collision accidents that have been ranked as major accidents (Montewka et al., 2014) may increase as the traffic flow keeps rising, and such a relationship has been verified in a study targeted to the Gulf of Finland (Viertola, 2013). Moreover, according to the collision probability model proposed by Montewka et al. (2010), heavy vessel traffic in intersection areas is more likely to give rise to collision accidents. In waterways where bridges are densely located, contact (ship collides with offshore structures or bridges) occurs more frequently (Pedersen, 2002; Zhang and Chen, 2010). And this is extremely obvious in Wuhan where seven bridges are densely located in a waterway range of about 60 km. However, these navigational environment factors should be adjusted when comparing the effectiveness of maritime safety control in other waterways.

In regard to the effectiveness of maritime safety control, DEA may be appropriate since it has been used extensively in performance evaluation with multiple inputs and outputs variables. It can provide a relative efficiency indicator of the assessed units, which is the ratio of weighted outputs to weighted inputs. The unit used is usually called a decision making unit (DMU). Three

Table 1
Influencing variables on maritime safety.

Ship condition	Maritime regulatory system	Human reliability	Navigational environment
Vessel age (Li et al., 2014)	Vessel traffic service (Viertola, 2013)	Human fatigue (Akhtar and Utne, 2014)	Current, wind, visibility (Balmat et al., 2009; Zhang et al., 2013)
Vessel size (Li et al., 2014)	International safety management (Knapp and Van de Velden, 2011; Batalden and Sydnes, 2014; Viertola, 2013; Karahalios, 2014; Bhattacharya, 2012)	Experience of navigation crew (Prabhu Gaonkar et al., 2013; Yang et al., 2013)	Traffic flow (Viertola, 2013)
Vessel type (Li et al., 2014)	Port state control inspection (Hänninen and Kujala, 2014)	Situation assessment (Hänninen and Kujala, 2012)	Geographical environment (Li et al., 2014)
Classification sociality (Li et al., 2014)	Safety management system (Akyuz and Celik, 2014)	Action to avoid accident (Hänninen and Kujala, 2012)	Seasonality (Li et al., 2014)
Mechanical failure (Hänninen and Kujala, 2012)	Convention on the Safety of Life at Sea (Viertola, 2013)	Crew collaboration quality (Yang et al., 2013)	Time of day (Balmat et al., 2009; Zhang et al., 2013; Li et al., 2014)
Navigation equipment failure (Hänninen and Kujala, 2012)	International convention on standards of training, certification and watch keeping for Seafarers (Viertola, 2013)	Adequacy of training (Yang et al., 2013)	Offshore structures (Pedersen, 2002)

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