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Use of fuzzy rule-based evidential reasoning approach in the navigational risk assessment of inland waterway transportation systems

Di Zhang [a,b,1], Xinping Yan [a,b], Jinfen Zhang [b], Zaili Yang [c,*], Jin Wang [c]

[a] National Engineering Research Center for Water Transport Safety, Wuhan 430063, China
[b] Intelligent Transport Systems Research Center, Wuhan University of Technology, Wuhan 430063, China
[c] Liverpool LOgistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, L3 3AF, UK

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ABSTRACT

A novel approach incorporating a fuzzy rule base technique and an Evidential Reasoning (ER) algorithm is applied to conduct the navigational risk assessment of an Inland Waterway Transportation System (IWTS). A hierarchical structure for modeling IWTS hazards (hazard identification model) is first constructed taking into account both qualitative and quantitative criteria. The quantitative criteria are converted to qualitative ones by applying a fuzzy rule-based quantitative data transformation technique, which enables the use of ER to synthesize the risk estimates from the bottom to the top along the hierarchy. Intelligent Decision System (IDS) Software is used for facilitating risk synthesis and estimation. The proposed method is tested in a case study to compare the navigational safety levels of three different regions in the Yangtze River.

1. Introduction

An Inland Waterway Transportation System (IWTS) is a complex and dynamic system in which various factors influencing each other increase the difficulty to assess its navigational risk (Dobbins and Jenkins, 2011; Zhang et al., 2013). Furthermore, uncertainties are involved when evaluating the navigational risk of an IWTS because objective data is sometimes incomplete and its collection is costly and time consuming, especially in the situation of taking into account the factors involving human and management aspects. Thus, a novel method utilizing Fuzzy Rule-Based Evidential Reasoning (FRBER) is adopted and further applied in the case study of the Yangtze River in this paper.

FRBER is implemented because it well describes the "riskiness" of the system for each combination of input variables (Bowles and Pelaez, 1995). Fuzzy rules are usually more conveniently formulated in linguistic terms than in numerical terms. They are often expressed as "If–Then" rules, which can be implemented by fuzzy conditional statements. The Evidential Reasoning (ER) approach is suitable for modeling subjective credibility induced by partial evidence (Yang and Xu, 2002). The kernel of this approach is an ER algorithm produced on the basis of the Dempster–Shafer (D–S) theory. The algorithm can be used to aggregate criteria of a multilevel structure. The ER has been widely used in industries such as engineering and management for decision making purposes (Liu et al., 2013, 2008; Chin et al., 2009; Ren et al., 2008; Lam et al., 2007).

The main aim of this paper is to conduct the quantitative navigational risk estimation of an IWTS via evaluating each Significant Influencing Factor (SIF) in the system and aggregating the estimations to obtain the overall risk estimate using the ER approach. In a preliminary study (Zhang et al., 2012), a risk hierarchical structure of an IWTS was established and the SIFs were identified through an Analytic Hierarchy Process (AHP) approach. This paper further investigates assessment grades for each criterion, converts quantitative criteria to qualitative ones by employing a rule-based technique and applies the ER approach to synthesize the risk estimates. A case study of the Yangtze River is used based on the hierarchical structure to demonstrate the applicability of the proposed approach in the navigational risk estimation of an IWTS.

2. Background

2.1. Evidential reasoning approach

ER was developed in the 1990s to deal with Multiple Criteria Decision Making (MCDM) problems under uncertainty. The ER

* Corresponding author.
E-mail addresses: zhangdi@whut.edu.cn (D. Zhang), xpyan@whut.edu.cn (X. Yan), zhangjinfen2000@126.com (J. Zhang), z.yang@ljmu.ac.uk (Z. Yang), j.wang@ljmu.ac.uk (J. Wang).
[1] Tel.: +86 27 86581899.

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Table 1
The hierarchical model of IWTS safety (Zhang et al., 2012).

Goal	Level 1	Level 2	Level 3
IWTS Safety (1.00)	Human (0.43)	Qualification (0.37) Experience (0.15) Safety Awareness (0.48)	
	Vessel (0.21)	Seaworthiness (0.41) Vessel Age (0.30) Tonnage (0.29)	
	Environment (0.24)	Natural (0.31)	Visibility (0.45) Wind (0.34) Current (0.21)
		Navigational (0.69)	Channel Dimension (0.65) Traffic Volume (0.09) Navaid (0.26)
	Management (0.12)	MSA (0.48) Shipowner (0.52)	

algorithm is based on the decision theory and the D–S theory of evidence, which is well suited for handling incomplete assessment of uncertainty (Yang, 2001; Yang and Singh, 1994). The algorithm can be used to aggregate criteria of a multilevel structure.

ER is widely used in many applications such as engineering design, system safety, risk assessment, organizational self-assessment and supplier assessment (Chin et al., 2009; Liu et al., 2008; Ren et al., 2008; Lam et al., 2007). ER has the following useful properties (Sönmez et al., 2001; Yang and Xu, 2002):

- It is difficult to deal with both quantitative and qualitative criteria under uncertainty, however ER provides an alternative way of handling such information systematically and consistently.
- The uncertainty and risk surrounding the problem can be represented through the concept of Degree of Belief (DoB).
- Both complete and incomplete information can be aggregated and modeled using a belief structure.
- The ER algorithm is integrated into a software package called Intelligent Decision System, IDS (Xu and Yang, 2005). It is a graphically designed decision support tool. The IDS allows Decision Makers (DMs) to build their own models and input their own data.

2.2. Fuzzy rule base technique

An important point of dealing with uncertainty came in 1965 with the publication of a fuzzy logic-based paper by Zadeh (1965). Fuzzy logic is an extension of classical Boolean logic from crisp sets to fuzzy sets. Fuzzy logic is the first new method of dealing with uncertainty since the development of probability. Fuzzy logic has various fuzzy techniques which can be used in uncertainty treatment, notably fuzzy sets and fuzzy rule bases. The application of these fuzzy logic techniques depends on the contexts to be modeled. They are widely used in many applications (Zadeh, 1987; Yang et al., 2012).

2.3. Research origin

The navigational safety of an IWTS has attracted great concern from academics and industrialists. Despite the use of fuzzy rule base and ER in the shipping industry, it has not been applied in the area of IWTS risk management. A feasible methodology is proposed in the following sections in order to demonstrate the applicability of ER and fuzzy rule base for the navigational IWTS risk assessment. Furthermore, the navigational risk of the Yangtze River, which is in a high uncertain situation, is evaluated using the method for the very first time.

3. Modeling of IWTS

In a preliminary study (Zhang et al., 2012), a hierarchical structure for IWTS modeling was developed and shown in Table 1. The IWTS safety is set as the goal of assessment. The elements in Level 1 are set to be Human, Vessel, Environment and Management. Each element in Level 1 is investigated based on its associated elements/factors given in Level 2 and Level 3. These elements/factors are chosen because they are regarded as the most significant ones associated with major causes which lead to marine accidents of the IWTS. The selection of such elements is conducted based on extensive discussions with experts in the area. The pairwise comparisons in each level of the hierarchical structure in terms of relative importance to navigational risk were carried out. The weighting vectors of the elements in each level were obtained and presented as the numerical values in Table 1 accordingly.

Three domain experts were interviewed for identifying the factors and evaluating their weights. They represented the major personnel who were involved in the navigational risk analysis in the Yangtze River. Simultaneously, they also possessed diversified interests and perception about how the navigational safety of the river can be evaluated and managed. The three experts' details are shown as follows:

- Expert No. 1: An experienced seafarer with experience of more than 5 years as a master onboard.
- Expert No. 2: A professor engaged in maritime research for more than 15 years.
- Expert No. 3: A senior officer from Chang Jiang Maritime Safety Administration (MSA).

4. Methodology

The following steps are developed in order to carry out the navigational risk estimation of IWTS.

Step 1: All the criteria (elements) in the hierarchical structure (Table 1) are assigned assessment grades. These assessment grades could be either qualitative or quantitative.

Step 2: The quantitative criteria in the hierarchy are represented by a fuzzy rule base. All of them are transformed into qualitative ones using a rule-based information transformation technique.