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Accident analysis model based on Bayesian Network and Evidential Reasoning approach

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A B S T R A C T

In this paper, an accident analysis model is proposed to develop the cost-efficient safety measures for preventing accidents. The model comprises two parts. In the first part, a quantitative accident analysis model is built by integrating Human Factors Analysis and Classification System (HFACS) with Bayesian Network (BN), which can be utilized to present the corresponding prevention measures. In the second part, the proposed prevention measures are ranked in a cost-effectiveness manner through Best-Fit method and Evidential Reasoning (ER) approach. A case study of vessel collision is analyzed as an illustration. The case study shows that the proposed model can be used to seek out accident causes and rank the derived safety measures from a cost-effectiveness perspective. The proposed model can provide accident investigators with a tool to generate cost-efficient safety intervention strategies.

1. Introduction

When an accident occurs, it is important to understand the root cause in order to take effective preventive measures. Accident analysis always implies an accident model is a set of assumptions of what the underlying "mechanisms" are (Hollnagel, 2002). An accident model is an abstract conceptual representation of the occurrence and development of an accident; it describes the way of viewing and thinking about how and why an accident occurs (Huang, Ljung, Sandin, & Hollnagel, 2004). Accident model is also a very important process for providing input to the development of proactive and cost-effectiveness safety measures (Psarros, Skjong, & Vanem, 2010).

There are extensive literatures about accident model, most of which analyzes accidents using conceptual representation or summary statistics. For example, Wang, Pillay, Kwon, Wall, and Loughran (2005) carried out marine accident analysis to determine the most common causes of accidents on fishing vessels using accident data collected from the Marine Accident Investigation Branch. They carried out a statistical study of accident type, deaths and vessels lost in period from 1994 to 1999, which showed that there was a real safety problem in the fishing vessel industry. Similarly, Toffoli, Lefevre, Bitner-Gregersen, and Monbaliu (2005) investigated 270 ship accidents reported as being caused by bad weather to contribute toward the definition of adequate warning criteria. Antão, Almeida, Jacinto, and Soares (2008) analyzed the sequence of events leading to accidents using historical data. Summary statistics are important but not sufficient to explain the accident. However, the existing accident models lack the capability of proposing and ranking cost-efficient safety measures in preventing the occurrence of accidents. To improve the existing models, this paper presents an extended accident analysis model by integrating 4 methods which consist of Human Factors Analysis and Classification System (HFACS), Bayesian Network (BN), Best-Fit and Evidential Reasoning (ER) method.

HFACS is a reliable human error analysis method that is able to assist investigators in the identification of human and organizational factors and their relationships in an accident (Wiegmann & Shappell, 2003). However, HFACS remains as a qualitative model. This weakness is overcome by the quantitative calculation of BN in this study. At the same time, the HFACS' 4-level structure provides a systematic guideline in the construction of BN to model how

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Nomenclature

BN	Bayesian Network
CPT	Conditional probability table
HFACS	Human Factors Analysis and Classification System
CBA	Cost–Benefit Analysis
ER	Evidential Reasoning
FSA	Formal safety assessment
DAG	Directed acyclic graph
AHP	Analytic Hierarchy Process
CAF	Cost of Averting a Fatality
GCAF	Gross Cost of Averting a Fatality
NCAF	Net Cost of Averting a Fatality

human errors are related to form a network. With a hierarchy of nodes and states defined, BN, which represents the relationship among the human errors, can be constructed. In the HFACS model, human errors at a particular level directly influence human errors at the next lower level. This relationship depicted in the HFACS will be mapped onto the BN via its graphical representation with edges connecting nodes at a particular level to those located one level below. The BN is systematically constructed with the help of the HFACS' hierarchal structure.

The purpose of CBA is to compare the costs and benefits associated with the implementation of safety measures. There are many papers carrying out safety assessment using formal safety assessment (FSA) method, in line with well-established cost-effectiveness criteria (IMO, 1997; Norway, 2000). For instance, Lois, Wang, Wall, and Ruxton (2004) selected cost-effectiveness risk control options after CBA using risk matrix approach and expert judgment. Psarros et al. (2010) also used FSA to investigate cost-effectiveness criteria whether can be used to evaluate safety measures. Vanem and Ellis (2010) presented an evaluation of the cost-effectiveness of a novel passenger monitoring system using FSA. Their analysis found that the cost-effectiveness criterion could be considered as the best candidate. Evidence showed that the cost-effectiveness approach was practical by including examples of successful applications in actual risk assessments. However, some experts pointed out that CBA, as suggested for use in FSA, was not a precise science but a way of evaluation. It might not be used mechanistically, but only as a consulting instrument in decision making (Wang & Foinikis, 2001). In previous works, common limitations were present when carrying out CBA, which mainly came from unavailability of data and uncertainty. To deal with it, Yang, Wang, Bonsall, and Fang (2009) proposed a subjective security-based assessment and management framework using fuzzy evidential reasoning (ER) approach. Several types of uncertainty such as ignorance and fuzziness can be consistently modeled using the ER method (Guo, Yang, Chin, & Wang, 2006). The ER approach provides a procedure for aggregating calculations, which can preserve the original features of multiple attributes with various types of information. It provides a solution for processing subjective risk assessment possibly with academic bias resulting from various opinions of different individuals. However, these works paid little attention to the calculation of risk reduction achieved by implementing the safety measures. In this paper, an ER-based CBA method considering risk reduction is proposed to combine CBA with risk assessment.

Lessons learned from accidents are important for identifying weaknesses in the present system and avoiding them in future (European Communities, 2001). For existing accident models, the quantitative analysis for accidents and cost-effectiveness analysis for safety measures are not sufficient. As a response, an extended accident analysis model is constructed to seek accident causes and propose cost-effectiveness safety measures in this paper. The remainder of this paper is organized as follows: In Section 2, an accident analysis model is constructed and illustrated in detail. Section 2.1 and Section 2.2 present how to analyze accidents by integrating HFACS with BN. Section 2.3 carries out cost-effectiveness assessment of the proposed safety measures using Best-Fit method and ER approach. In Section 3, an illustrative study is conducted to demonstrate the feasibility of applying the model in the area of vessel collision.

2. Accident analysis model

The proposed accident analysis model consists of two parts. The first part of the model investigates accident causes and proposes corresponding safety measures using a two-phase accident analysis framework (Wang, Roohi, Hu, & Xie, 2011). The second part of the model ranks the proposed safety measures using Best-Fit method and ER approach from a cost-effectiveness perspective. The model is summarized as shown in Fig. 1.

In this model, there are four main steps:

1. Analyze accidents using HFACS &BN to identify/rank the main causes of accidents.
2. Propose corresponding safety measures in line with the rank of causes, and then calculate the reduction of accident probability after implementing each safety measure using BN.
3. Carry out CBA using Best-Fit method and ER approach.
4. Rank the proposed safety measures based on the reduced risk and CBA results.

2.1. Accident analysis

This section presents a two-phase accident analysis framework, which is shown in Fig. 2, to assess human and organizational errors in both qualitative and quantitative manners. In the first phase, the qualitative analysis of an accident is carried out to analyze various human errors using HFACS. In the second phase, the human errors identified in the first phase are quantitatively analyzed. This quantification process is achieved using BN, which enables quantification of the relationships among the human errors identified, enhancing the power of HFACS.

The application of HFACS provides a systematic guideline for accident investigations. Investigation starts from defining the accident of concern and proceeds upwards to identify active errors. This continues till organizational influences errors are identified. The systematic level-by-level procedure ensures that as comprehensive human errors as possible are uncovered. They are the lessons to be learnt from the accident. This helps to improve the current situation under which marine accident surveyors usually explain an accident from some pieces of experiential evidences (Celik, Lavasani, & Wang, 2010).

BN is a probabilistic graphical model that represents a set of random variables and their conditional independencies via a directed acyclic graph (DAG) (Detcher & Mateescu, 2004). Conditional probability table (CPT) elicitation is a complicated issue due to a large number of judgments required to quantify the relationships of BN (Rajabally, Sen, Whittle, & Dalton, 2004). In this paper, Analytic Hierarchy Process (AHP) and the decomposition method is used to estimate CPT for BN nodes.

Suppose that a node X (with k states $x_1, x_2, \ldots x_k$) has n parents ($T^{(1)}, T^{(2)}, \ldots T^{(n)}$). The determination of the conditional distribution