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A risk-based modelling approach to enhance shipping accident investigation

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ABSTRACT

This paper developed a risk-based modelling approach to enhance the execution process of shipping accident investigation (SAI). Specifically, the paper addressed a fuzzy extended fault tree analysis (FFTA) that combines the effects of organizational faults and shipboard technical system failures under a unique risk assessment scheme. The case study illustrates that a novel idea behind the proposed methodology allows relevant accident investigators to clarify the probability of technical failures, operational misapplications, and legislative shortages leading to the shipping accident. The current SAI reports can be extended with an integrated risk assessment section to formulate integrated strategies along with risk control measures onboard ships. Since the consequences of shipping accidents are still a global concern, the paper addresses integration of a FFTA into SAI reports to ensure a consistent database and subsequent decision aid to accident analysis and prevention efforts in the maritime transportation industry.

1. Introduction

Over the last decade, international maritime authorities have made significant efforts to promote safety at sea in the shipping transportation industry (O'Neil, 2003; Hetherington et al., 2006). Especially, the International Maritime Organization (IMO) encouraged the establishment of a safety management system (SMS) in shipping companies in accordance with the international management code for the safe operation of ships and for pollution prevention (ISM Code) that was a critical milestone for maintaining a legislative control in shipping (Goulielmos and Tzannatos, 1997). Nevertheless, the recently published statistical reports (Roberts and Marlow, 2002; O'Neil, 2003; Darbra and Casal, 2004) have highlighted that there are still an enormous number of shipping accidents. Furthermore, the consequent impacts of shipping accidents vary in a greater scope, including loss of life, extensive marine pollution, damage to ship or its cargo, and others (Hansen et al., 2002; Wang, 2002). In detail, human errors, technical and mechanical failures, and environmental factors are commonly underlined factors leading to shipping accidents with different percentages. In global relevance, there is no certain consensus on the statistical distribution on the causes of shipping accidents due to the different viewpoints of accident analysis and investigation approaches. Thus, prevention of shipping accidents is still a focal matter of maritime interests.

In spite of the increasing regulatory control and innovative trend of marine technology, a question has been arisen as to why the rate of shipping accidents has not been reduced to the desired levels. The system complexity and automation (Busby and Chung, 2003), human errors (Er and Celik, 2005), human-centred system design (Lin et al., 2007), and potential design-based failures (Celik and Er, 2007; Celik, 2008), are different perspectives for the problem regarding the reduction of the shipping accidents. As a novel response to such phenomenon, this paper offers an analytical foundation for the shipping accident investigation (SAI) process enabling to satisfactory feedbacks for relevant organizations.

1.1. Progressing through shipping accident investigation

SAI is an extremely significant task for increasing safety of merchant ships. Hence, a comprehensive investigation procedure is necessary to have insight in the active and latent factors contributing to the occurrence of the investigated shipping accident events. Otherwise, the feedbacks from the accident investigation reports to the maritime community would be insufficient. Based on the findings of the shipping accident reports, various preventive/corrective actions such as the improvement of qualifications and training requirements (McCarter, 1999), enhancement of operational conditions and workspace layouts (Theodosiou and Sapidis, 2004), and SMS redesigns (Celik, 2009) could be taken into account. The motivating idea behind this paper is to find out how the utility of a SAI report can be appreciated in a methodological manner to ensure further improvements in safety at sea.

To underline the cited proposals towards enhancing the SAI process, a critical review through a few relevant papers in the literature is conducted. Anderson (1983) suggested a genuine idea to solve design problems onboard ships via using the data from

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accident reports. To increase the design standards, Wang et al. (2002) developed a model to measure the structural performance of a ship in an accident. Furthermore, Goulielmos and Giziakis (2002) used a model based on a complexity theory to increase the effectiveness of the ISM Code as a solution for prevention of marine accidents in a wide manner. The paper gives the correlations between implementation performance of maritime regulations and shipping accident prevention. To underline the environmental factors leading to shipping accidents, Toffoli et al. (2005) undertook an investigation of shipping accidents particularly reported as being due to bad weather conditions to contribute towards the coherent definition of the adequate warning criteria. From a technical perspective, Wang et al. (2005) carried out an analysis to determine the most common causes of accidents on fishing vessels to encourage safety assessment of fishing vessels. The detailed analysis of container ship accidents has shown that safety management practices, safety training, and job safety are the most significant factors among the safety dimensions (Lu and Tsai, 2008). Antão and Guedes Soares (2008) analysed a sequence of events leading to the accident. Moreover, the associated latent or causal factors for ocean-going commercial vessels and high-speed craft (HSC) were explored. From the analysis, the bridge personnel and operations were identified as the key factor in the pattern of causal factors associated with HSC accidents compared with the more traditional ocean-going ships. Recently, Celik and Cebi (2009) integrated a Fuzzy Analytical Hierarchy Process (FAHP) into a traditional framework of the Human Factors Analysis and Classification System (HFACS) (Shappell et al., 2007) to provide an analytical foundation and group decision-making ability, thus allowing quantitative assessment of a SAI process.

1.2. Linking up to quantitative risk modelling

The critical review on shipping accident analysis clearly indicates that the current approaches have only targeted certain perspectives (i.e. human error, mechanical failure, etc.). However, the occurrence of shipping accidents commonly depends upon various shortfalls in different segments of safety barriers. There is an urgent need for a new approach capable of addressing this issue. The principal focus of this paper is to provide an analytical framework based on a fuzzy fault tree analysis (FFTA), which aims at clarifying the probability and importance of the various factors leading to a shipping accident. The model scope will cover to estimate and control the probable risks associated with the operational environment of a traditional merchant ship. In addition, it also incorporates the reflection of managerial responsibilities to operational level in some certain points such as legislative implementation. In doing that, the study has been expected to ensure great potential and satisfactory feedbacks to maritime organizations in accident analysis and prevention efforts.

2. Research methodology

This section introduces the background of the proposed research methodology to adapt a new approach into the SAI process.

2.1. Background

A fault tree analysis (FTA) is a logical and diagrammatic method to evaluating the occurrence probability of an accident resulting from sequences of faults and failure events. A FTA is useful for understanding the mode of occurrence of an accident logically. Furthermore, given the failure probabilities of system components, the occurrence probability of the top event (TE) can be obtained. Traditionally, it is usually assumed that the basic events within a fault tree are independent of each other and could be represented in terms of probabilistic numbers. With this assumption, quantitative analyses of fault trees are usually performed by considering two cases: (1) fault trees without repeated event, and (2) fault trees with repeated events (Andrews and Moss, 2002; Henley and Kumamoto, 1981).

2.1.1. Fault trees without repeated events

In the event that the fault tree for a TE "Z" contains independent basic events which appear only once in the tree structure, the TE probability can be obtained by working the basic event probabilities up through the tree. In doing so, intermediate gate event ("AND" or "OR") probabilities are calculated by starting at the base of the tree and working upwards until the TE probability is obtained. Fig. 1 depicts the symbolic representation of "AND" and "OR" gates in a FTA.

For an "AND" gate event, the following equation can be used to obtain the occurrence probability of "Z":

$$P = \prod_{i=1}^{n} p_i \tag{1}$$

where P is the occurrence probability of the TE, p_i denotes the occurrence probability of basic event i, and n is the number of the basic events associated with the "AND" gate. For an "OR" gate event, the occurrence probability of "Z" can be determined as follows:

$$P = 1 - \prod_{i=1}^{n} (1 - p_i) \tag{2}$$

where p_i denotes the failure probability of basic event i, and n is the number of the basic events associated with the "OR" gate.

2.1.2. Fault trees with repeated events

When a fault tree has basic events which appear more than once, the methods most often used to obtain the TE probability utilise the minimal cut sets (MCs). A MC is a collection of basic events. If all these events occur, the TE is guaranteed to occur; however, if any basic event does not occur, the TE will not occur. Suppose a fault tree has MCs represented by MC_i, $i = 1, \ldots, n_c$. Then the TE "Z" exists if at least one MCs exists (Andrews and Moss, 2002).

$$Z = MC_1 + MC_2 + \cdots + MC_{n_c} = \bigcup_{i=1}^{n_c} MC_i \tag{3}$$

An exact evaluation of the TE occurrence probability can be obtained as follows:

$$\begin{aligned} P(T_Z) &= P(MC_1 \cup MC_2 \cup \cdots \cup MC_N) \\ &= P(MC_1) + P(MC_2) + \cdots P(MC_N) - (P(MC_1 \cap MC_2) \\ &\quad + P(MC_1 \cap MC_3) + \cdots P(MC_i \cap MC_j) \cdots) \cdots \\ &\quad + (-1)^{N-1} P(MC_1 \cap MC_2 \cap \cdots \cap MC_N) \end{aligned} \tag{4}$$

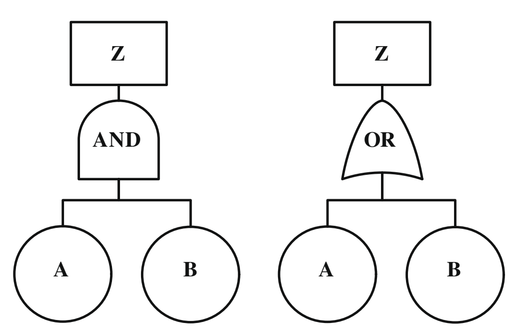

Fig. 1. Symbolic representation of "AND" and "OR" gates in a FTA.