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Use of HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters

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ABSTRACT

With the global warming and a large amount of sea ice melting, the available Arctic Sea Route has greatly enhanced the value of Arctic shipping. Ship operations under icebreaker assistance have become an essential way to facilitate the safe navigation of merchant vessels sailing through the Arctic Sea Route in ice-covered waters, but they can also put the crew and the ship in danger caused by a possible collision between the assisted ship and the icebreaker. In this paper, a dedicated Human and Organizational Factors (HoFs) model of ship collision accidents between an assisted ship and an icebreaker is developed and analyzed with the aim to identify and classify collision risk factors. First, a modified model of the Human Factors Analysis and Classification System (HFACS) for collision accidents between a ship and an icebreaker in ice-covered waters is proposed, which helps to analyze ship collision reports. Then, a Fault Tree Analysis (FTA) model is utilized to analyze the fundamental collision risk factors according to the statistical analysis of accident reports and expert judgments based on the HFACS-SIBCI model. Finally, qualitative analysis is carried out to analyze collision risk factors under icebreaker assistance, where Risk Control Options (RCOs) are formulated. An important guidance for the risk control of ship collisions during icebreaker assistance in ice-covered waters is provided for lawmakers and shipping companies.

1. Introduction

With the global warming and a large amount of sea ice melting, the extremely valuable Northern Sea Route (NSR, 2017) has led to an increased interest in Arctic activities of ships (Beveridge., 2016; Fu et al., 2017). In this area, navigational operations under icebreaker assistance are key to the success of the safe navigation of merchant vessels (Zhang et al., 2017; Montewka et al., 2015; Valdez Banda et al., 2015). It is very difficult to ensure the safety of navigation in Arctic waters when vessels sail independently facing harsh conditions, such as the presence of sea ice, low temperatures, electromagnetic interference, and other complex environmental conditions (Stoddard et al. 2015; Goerlandt et al., 2016; Fu et al., 2017; Khan et al., 2018; Ostreng et al., 2013). At the same time, ordinary vessels lack the capability of ice-breaking, so they are unable to sail independently in a harsh ice environment, which can easily lead to ice accidents (Kum et al., 2015; Fu et al., 2016). Hence, navigational operation under icebreaker assistance represents a typical model of ship operation in ice-covered waters. In 2016, 62.5% of General Cargo Carriers were under icebreaker assistance in the ice-covered waters of the NSR which provided by Northern Sea Route Information Office (Transit Statistics 2011–2016). In addition, icebreaker assistance operations also play an essential role in the ice-covered waters of the Baltic Sea in winter. The numbers of vessels under icebreaker assistance during the icebreaking season in the Baltic Sea in different years are shown in the following picture taken from *Baltic Sea Icebreaking Report 2007–2016* provided by the *Baltic Organization* (see Fig. 1) (Baltic Organization, 2017).

Icebreaker assistance is a widespread method used in navigation in ice-covered waters. Navigational operations under icebreaker assistance are organized into four identified icebreaker operations: *Escort operations, Convoy operations, Breaking a ship loose operations* and *Towing operations* (Goerlandt et al., 2017; Valdez Banda et al., 2015), where escort operations and convoy operations are key to the success of the safe navigation of merchant ships. Convoy operations are similar to

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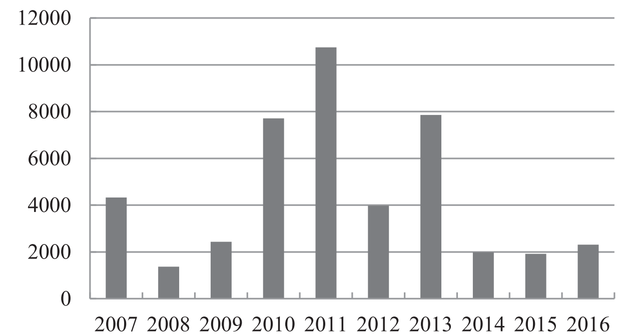

Fig. 1. The number of assisted ships under icebreaker assistance in the Baltic Sea in wintertime (2007–2016). Source: Baltic Sea Icebreaking Report (2007–2016).

escort operations, where several ships follow an icebreaker at a short distance in case the ice channel is filled with ice cakes (Zhang et al., 2017). Escort and convoy operations under icebreaker assistance reduce the risk of frequent accidents, such as ice collisions and propeller or rudder damage. Nevertheless, collision accidents do occur between icebreakers and assisted ships. The statistics of accidents occurred in ice-covered waters of Russian sea area (Goncharov et al., 2011; Loanov et al., 2013) and Finnish sea area (Valdez Banda O.A. 2017) are presented in Fig. 2. It can be seen that in Finnish sea area the percentage of collisions is 48% out of all accidents, and 95% out of all accidents under icebreaker assistance. In addition, in Russian sea area, collisions during escort operation account for 55% under similar assistance conditions. Despite the differences between Finnish and Russian sea areas, the statistics of accidents indicate that ship to icebreaker collision is the most typical accident type in ice-covered waters.

Collision risks between icebreakers and assisted ships sailing within a close distance cannot be ignored in ice-covered waters. In the scientific literature, the risks of collisions under icebreaker assistance are different from other ship collision accidents, estimated to be higher in ice-covered waters than in open waters (Zhang et al., 2014; Franck and Holm Roos, 2013; Sulistiyono et al., 2015). Accordingly, collision risk factors should be investigated under specific conditions. There exists literature on accidents analysis in open waters and ice-covered waters. The risks of ship collisions are assessed, which is of signification importance for narrow, shallow and busy waterways (Qu et al., 2011; Klanac et al., 2010; Zhang et al., 2016). Furthermore, the analysis of the risks of navigational operations in ice-covered waters suggests that escort and convoy operations under icebreaker assistance are quite dangerous operations performed in the ice-covered waters. Overall, collisions between assisted ships and icebreakers present the most significant risk (Valdez Banda et al., 2016; Goerlandt et al. 2017). A root cause analysis method is presented to analyze the risks of collisions and grounding in Arctic waters, which aims at proposing a recommendation to reduce the occurrence probability based on fuzzy fault tree analysis (Kum and Sahin, 2015). An Arctic shipping accident scenario is analyzed to identify essential accident risk factors in a potential accident scenario (Afenyo et al., 2017). Risk analysis models of ships stuck in ice are proposed (Fu et al., 2016; Fu et al., 2017; Montewka et al., 2015). Another line of work focuses on the application of risk-based design principles to Arctic shipping (Bergström et al. 2015, Ehlers et al. 2017).

However, these studies are limited in terms of the risk analysis of typical operational conditions or accidents, such as collisions between ships or a ship and ice, grounding accidents, and ship stuck incidents in ice-covered waters, not focusing on collision risk factors during icebreaker assistance operations in ice-covered waters.

Icebreaker assistance operations in ice-covered waters refer to a team navigation system consisting of an icebreaker and an assisted ship. The detuning of the navigational conditions between the icebreaker and the assisted ship is the cause of a collision accident after a change in the team navigational system. Accordingly, human and organizational factors are main factors contributing to the occurrence of collision accidents. In the scientific literature, a number of human error analysis models and frameworks have been proposed to aid in the understanding of faults and errors related to human and organizational factors in complex systems where such accidents occur, such as the four stage information processing model presented by Wickens et al. (1988), the SHEL model (Edwards, 1972), the multiple SHEL model (IMO, 1999), and the GEMS (Generic Error Modeling System) proposed by Reason et al. (1990). These models and frameworks focus on the human errors of operators.

The framework of the Human Factors Analysis and Classification System (HFACS) was presented by Wiegmann et al., 2003, which was used to classify and identify contributing factors in accident factors analysis. The HFACS-framework was used to analyze maritime accidents (Chauvin et al., 2013; Chen et al., 2013), potential impact of unmanned vessels on marine transportation safety (Wróbel et al., 2017), grounding accidents (Mazaheri et al., 2015), road traffic accidents (Baysari et al., 2008; Reinach and Viale, 2006; Patterson et al., 2010), railway accidents (Zhan et al., 2017), and classify and identify fundamental risk factors based on accident reports.

In particular, a systematic and multi-factorial analysis of collision factors under icebreaker assistance is presented, which aims at identifying and classifying collision risk factors. The research relies on the HFACS and the FTA, which are utilized to identify and classify collision risk factors that are mentioned in reports of accidents between icebreakers and assisted ships in ice-covered waters. First, a collision risk factors analysis method for ship collision accidents between assisted ships and icebreakers in ice-covered waters, named the HFACS-SIBCI model, is proposed. Then, a Fault Tree model is proposed using the statistical analysis of collision risk factors according to accident reports

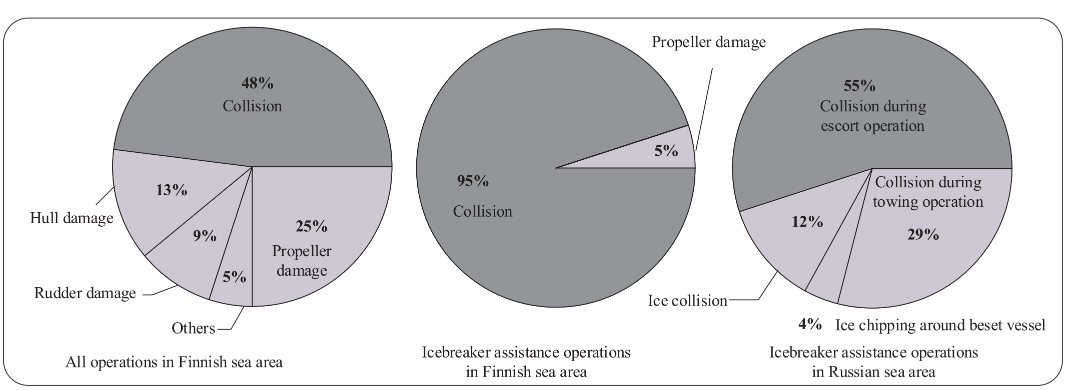

Fig. 2. The statistics of accidents occurred in ice-covered waters in Russian Sea area (Goncharov et al., 2011; Loanov et al., 2013) and Finnish Sea area (Valdez Banda O.A. 2017).