Reliability Engineering and System Safety 156 (2016) 210–227

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

# Incorporation of human factors into ship collision risk models focusing on human centred design aspects

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A R T I C L E   I N F O

*Article history:*
Received 25 November 2015
Received in revised form
29 June 2016
Accepted 12 August 2016
Available online 18 August 2016

*Keywords:*
Collision risk analysis
Bayesian Networks
Event tree
Human factors
Human-centred design
Sensitivity analysis
FSA

A B S T R A C T

This paper presents an approach that more adequately incorporates human factor considerations into quantitative risk analysis of ship operation. The focus is on the collision accident category, which is one of the main risk contributors in ship operation. The approach is based on the development of a Bayesian Network (BN) model that integrates elements from the Technique for Retrospective and Predictive Analysis of Cognitive Errors (TRACEr) and focuses on the calculation of the collision accident probability due to human error. The model takes into account the human performance in normal, abnormal and critical operational conditions and implements specific tasks derived from the analysis of the task errors leading to the collision accident category. A sensitivity analysis is performed to identify the most important contributors to human performance and ship collision. Finally, the model developed is applied to assess the collision risk of a feeder operating in Dover strait using the collision probability estimated by the developed BN model and an Event tree model for calculation of human, economic and environmental risks.



## 1. Introduction

Probabilistic methods and formal methods for risk assessment have been used in the maritime industry for some time, as reviewed by Guedes Soares and Teixeira [18] and more recently by Guedes Soares et al. [19]. An important contribution to the general adoption of risk assessment techniques in the marine transportation sector occurred in the 90's when the International Maritime Association (IMO) has introduced the “Formal Safety Assessment” (FSA) methodology for use in the IMO rule making process [23,26].

Traditionally, FSA studies include comprehensive risk models developed to assess probabilities and consequences of specific accidental events using mainly Event tree models, which also allow the assessment of the effect of risk control measures. Seldom models were developed considering in more detail the causes of an accident, e.g. in form of Fault tree. However, risk models are in general complex and, as shown for instance by recent FSA studies, contain many dependencies between the technical systems and the human element, hardly possible to consider adequately in Fault and Event tree models. To cope with this complexity Bayesian Network (BN) models have been suggested and adopted in alternative to more classical methods in several FSA studies (e.g. [25]). In fact, the FSA on navigation safety of large passenger ships has used BN as the modelling tool.

So far, ship structure and systems were in focus when identifying risk reduction measures and accordingly human performance gained continuously more importance. This has been also confirmed by many studies that have identified an increasing contribution of human errors to ship accidents, as explained by Antão and Soares [3]. Hence, adequate modelling of human behaviour is of increasing relevance.

Several authors have studied and modelled the contribution of human and organisational factors to ship accidents [6,13]. In the vast majority of cases, incidents happened due to one of the following causes or a combination of them: Poor crew competence, fatigue, lack of communication, lack of proper maintenance, lack of application of safety culture and protocols or other procedures, inadequate training, poor situation assessment, stress [13,41,46]. Thus, reducing the occurrence of these causes will reduce the probability of accidents and therefore increase the safety for persons on board and to environment.

This paper is focused on improving the consideration of the human element (HE) in maritime quantitative risk analysis in order to: a) integrate human factor in a reliable manner into the risk framework of FSA; b) develop a method to assess crew performance in a risk related context; c) provide a tool for assessment of

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http://dx.doi.org/10.1016/j.ress.2016.08.007

Human Centred Design (HCD). Overall to provide viable solutions for the risk-based design process of ships and their systems.

The risk model presented in this paper has been developed in the EU project CyClaDes (Crew-centred Design and Operations of ships and ship systems, 2012 – 2015) for collision accident, which is a major risk contributor for various ship types and is mainly caused by human errors. The model considers an Event Tree that represents the consequences of a collision event and a BN developed to calculate the probability of collision and to model the basic factors that contribute to Officer of the Watch (OOW) competence, detection, assessment and action. Influencing parameters were based on the Performance Shaping Factors (PSF) of the TRACEr (Technique for the Retrospective and predictive Analysis of Cognitive Errors) taxonomy originally developed for Air Traffic Control [49], which was recently adapted to the maritime context [21] and used by Graziano et al. [16] to code and analyse a set of collision accidents.

The paper is structured as follows: a literature review with respect to the applications of Bayesian Networks in the maritime sector is presented in Section 2. The fundamental theory and the proposed collision risk model focusing mainly on the influence of Human Centred Design features are introduced in Section 3. Section 4 presents the results; in particular, the quantification and validation process of the BN, the sensitivity analysis conducted on the developed BN and the implementation of the collision probability in the framework of a complete risk analysis. Finally, important concluding points and observations derived by the analysis are drawn in Section 5.

## 2. Use of BN models in maritime risk assessments

Bayesian Networks (BNs) provide an important tool for analysis of complex phenomena with both deterministic and stochastic information and relationships. A Bayesian Network (BN) is a probabilistic graphical model representing a set of random variables and their conditional dependencies via a Directed Acyclic Graph (DAG) (e.g. [27]). Bayesian Networks can substitute both FTs and ETs used in more traditional risk models and have significant advantages over fault tree analysis for modelling complex dependent structures. BNs also permit inference based on observed evidence or evidences, thus allowing exploiting the model response under different scenario and can be used to identify most probable scenarios (i.e. one state from each variable of the network) given evidence on one or more variables.

Bayesian Networks have already been applied for various transport systems including maritime problems. Nevertheless, the number of published works with the application of BN modelling in the maritime field is still very scarce when compared with other industries. For instance, the works performed by Or and Kahraman [39], Pedrali et al. [43], Leva et al. [32], Eleye-Datubo et al. [10], Trucco et al. [51] and Norrington et al. [38]. Most of these studies are based on elicitation through experts' judgements and with low number of states per node. Typically, mainly binary states or canonical Noise-OR or Noise-AND are used for both reasons, reduction in the computational demand and aid on the elicitation process.

Later, Antão et al. [2] have used a BN framework for analysing maritime accidents. The data set consisted of 857 casualties from a 10-year period. The data record structure consisted of ship characteristics, accident type and consequences. The explanation of the accident was limited to a single so-called probable cause only. Even with this limited data important profiles for the different accident type could be established.

In the context of collision risk assessment, the most common approaches used to assess ship collision probability are based on the work of Fujii et al. [14] and MacDuff [35]. Their model was modified by Pedersen [42] and used extensively in safety assessment studies of navigation in European waters. According to Pedersen [42] the number of potential, or expected, collisions is defined as:

$$P = N_A \bullet P_c \tag{1}$$

where $N_A$ is the number of collision candidates and $P_C$ is the causation probability, or the probability of a collision candidate becoming a collision (e.g. [36]).

The number of collision candidates ( $N_A$) corresponds to the number of collisions if no evasive manoeuvres were made, and it depends on ship traffic properties in the area. The collision candidates can be estimated for a particular crossing of two waterways [42] or using directly Automatic Identification System (AIS) data with the concept of collision diameter defined by Pedersen [42], e.g. as done by Silveira et al. [50].

The causation probability ($P_c$) can be estimated using two approaches: the scenario approach or the synthesis approach. The scenario approach is used if the causation probability is calculated based on available accident data. The synthesis approach relies on the development of Bayesian Network models to estimate ($P_c$), i.e. the fraction of collision candidates failing to avoid the collision, which is typically affected by technical, environmental and human factors.

Bayesian Network models have been adapted to causation probability estimation, which vary both in the number and in the nature of their variables. For instance, Friis-Hansen and Simonsen [12] developed a software package called Grounding and Collision Analysis Toolbox (GRACAT), to estimate the probability of vessel collisions and groundings including damage evaluation. GRACAT uses in the calculation of the collision and grounding probabilities the method which is based on the models of Fujii et al. [14] and MacDuff [35]. The BN model for predicting the causation factor for ship–ship collisions was based on the network formulated by Friis-Hansen and Pedersen [11] but extended to model two ships, i.e. ship–ship collision situations. GRACAT software has been used for example in the collision risk estimation of the FSA study performed for the implementation of the VTMIS (Vessel Traffic Management and Information Services) system for the Gulf of Finland.

Another application of BN models for grounding and collision scenarios was undertaken by Norway in conjunction with the FSA on Large Passenger Ships [24]. In this study, risk models were developed for grounding and collision accidents for quantification of Risk Control Options (RCOs), in particular for the evaluation of the effect of ECDIS (Electronic Chart Display and Information System), ENC (Electronic Navigational Charts) and Track control. These BN models for the powered grounding and collision accident scenarios included human factors, technical factors, geographical and other external factors, chosen with the aim to reflect important risk contributors and to be able to evaluate the effect of RCOs. The analysis considered five scenarios that may lead to grounding with probabilities estimated based on expert judgement. Moreover, several factors were considered to influence the ability to perform the navigators' tasks, such as: a) Management factors; b) Working conditions and c) Personal factors that include the physical and mental state of the OOW (fatigue, stress level, intoxicated, etc.). For the collision scenarios, the modelling of loss of control of the vessel is more or less the same as for grounding, except that the interaction with the other vessel (give-way rules and practices, communication, etc.) was included.

Hanninen and Kujala [20] studied the influences of the variables in a Bayesian belief network model for estimating the role of human factors on ship collision probability in the Gulf of Finland.