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Bayesian network model of maritime safety management

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ABSTRACT

This paper presents a model of maritime safety management and its subareas. Furthermore, the paper links the safety management to the maritime traffic safety indicated by accident involvement, incidents reported by Vessel Traffic Service and the results from Port State Control inspections. Bayesian belief networks are applied as the modeling technique and the model parameters are based on expert elicitation and learning from historical data. The results from this new application domain of a Bayesian network based expert system suggest that, although several its subareas are functioning properly, the current status of the safety management on vessels navigating in the Finnish waters has room for improvement; the probability of zero poor safety management subareas is only 0.13. Furthermore, according to the model a good IT system for the safety management is the strongest safety-management related signal of an adequate overall safety management level. If no deficiencies have been discovered during a Port State Control inspection, the adequacy of the safety management is almost twice as probable as without knowledge on the inspection history. The resulted model could be applied to performing several safety management related queries and it thus provides support for maritime safety related decision making.

1. Introduction

Safety management is a subarea of organizational management. Its aim is to develop, plan, realize and follow operations for preventing accidents and minimizing risks related to the safety of people, environment or property. In the maritime domain, the International Safety Management (ISM) Code provides requirements for safety management systems (International Maritime Organization, 2013). The ISM Code is mandatory for all ships belonging to the scope of the International Convention for the Safety of Life at Sea (SOLAS) of International Maritime Organization (IMO), that is, the majority of internationally trading ships. To support the ISM Code, some particular sectors of the maritime transportation have launched their own additional safety management guidelines such as the Tanker Management Self-Assessment (TMSA) by The Oil Companies International Maritime Forum (OCIMF, 2008).

Safety management is a broad topic and covers several subareas. A model describing the elements of maritime safety management, how these elements interact, and how strongly safety management and safety are linked could provide useful information about the functioning of the safety management. It could serve as an assessment and monitoring tool and aid in continuous improvement and decision making when managing maritime traffic safety.

Previously several frameworks for assessing the effects of organizational aspects on risk or safety have been published within different domains (Embrey, 1992; Paté-Cornell & Murphy, 1996; Øien, 2001; Mohaghegh, Kazemi, & Mosleh, 2009; Roelen et al., 2003) and in the maritime transportation field (Trucco, Cagno, Ruggeri, & Grande, 2008). Components and the component connections of concepts closely related to safety management, such as the safety culture, have been mathematically described in other domains (dos Santos Grecco, Vidal, Cosenza, dos Santos, & de Carvalho, 2014) and on a coarse level in the maritime traffic (Håvold, 2005; Oltedal & McArthur, 2011; Ek, Runefors, & Borell, 2014). However, these have not addressed safety management per se. While studies such as Le Coze (2013) have investigated the elements of safety management and even qualitatively modeled their interdependencies (Hale, Heming, Carthey, & Kirwan, 1997), detailed quantifications of the maritime safety management subarea interactions seem to be lacking; the existing models provide rather limited means to comprehensive reasoning about the maritime safety management mechanisms and to the related decision-support. Furthermore, to the authors' knowledge, no safety management models based on the established safety management norms or standards have been published.

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To address the lack of quantitative decision-support tools for maritime safety management in the existing literature, this paper presents a Bayesian network based expert system which models the maritime safety management subarea qualities and their dependency patterns. In addition, the paper links the safety management to three maritime traffic safety indicators: maritime traffic accident involvement, conducting a violation or incident that has been reported by a Vessel Traffic Service (VTS) center, and deficiencies discovered in Port State Control (PSC) inspections. The aim of the model is to describe the current status of safety management on board ships navigating within Finnish waters. More specifically, it provides an expert-based probabilistic representation of maritime safety management norms while also considering the uncertainty related to the subareas and their links and the one between the experts. Moreover, by connecting the current status of safety management to the aforementioned accident and incident data, the model provides means to evaluate how informative these safety indicators are for assessing the state of the safety management and vice versa. The featured aspects the authors believe to be novel in this paper can be summarized as (1) the utilization of current norms and standards in establishing a maritime safety management model, (2) the application of Bayesian networks as the modeling technique to describe and reason about safety management, and in this case, the specifics of maritime safety management, and (3) the linking of an expert-based maritime safety management model to three data-based maritime safety indicators.

The rest of the paper is organized as follows. Section 2 describes the applied methods and input data in building the model. The resulting model and some findings derived with it are presented in Section 3, Appendix A and Appendix B. The Section 4 discusses the results further while also presenting an evaluation of the model validity. Finally, conclusions are drawn in Section 5.

2. Material and methods

2.1. Bayesian networks

A modeling technique that can present relatively complex, potentially but not necessarily causal dependencies and cope with uncertain and unobserved variables while also having a graphical dimension, is Bayesian belief networks (Pearl, 1988). A Bayesian network (BN) graphically represents the joint probability distribution of a set of discrete variables (Darwiche, 2009). The structure of a BN model is a directed graph, where the graph nodes reflect the model variables and the links between the nodes the direct variable dependencies. Each node consists of a finite number of mutually exclusive states. Each state has a probability of occurrence and it depends on the states of the variable's potential parent nodes, i.e., the variables with a direct link to the variable in question. BNs have been widely applied as the modeling approach when constructing an expert system including uncertainty, and they have been also utilized in several maritime traffic safety related studies (Trucco et al., 2008; Hänninen et al., 2014; Hänninen & Kujala, 2014a; Montewka et al., 2014). However, they have not been applied to reasoning the relationships among a number of maritime safety management related variables and further to modeling safety management connections to safety.

In this paper, the safety management and its dependencies with safety indicators are modeled with BNs. A separate BN is built for describing the safety management, which is then inserted as a submodel to a BN model including the safety indicators. Whereas the *Safety management* submodel parameters are based on expert opinion, the distributions for the indicators are learned from data. The following subsections describe the construction of these models in more detail.

2.2. Safety management model structure

The *Safety management* model variables represent various subareas of the maritime safety management. The subareas are selected based on content analyses of the ISM Code and two supplementary safety management descriptions, the Tanker Management Self-Assessment (TMSA) and list of safety management components derived by a group of experts based on a safety management framework proposed by Grote (2012). The analysis process for selecting the variables is not described here but is explained in detail in Valdez Banda, Hänninen, Lappalainen, and Kujala (2014).

Based on the analyses, the following set of 23 safety management subareas is selected as the variables of the *Safety management* BN model:

- Accident and incident reporting and analysis
- Communication
- Company responsibilities and authority
- Designated persons
- Documentation
- Emergency preparedness
- External audit
- Feedback
- Internal audit
- IT system for the safety management (a system used for collecting, storing and managing the information derived from the various safety management activities, e.g. work procedures, plans, programs, incident reports, audit results)
- Maintenance of the ship and equipment
- Management commitment
- Management review
- Master's responsibilities and authority
- No-blame culture
- Personnel awareness and involvement
- Planning
- Resources and personnel
- Safety and environmental protection policy
- Shipboard operations
- Status of the corrective actions
- Status of the preventive actions
- Training

Three mutually exclusive states, *good*, *average*, and *poor*, are assigned to each subarea variable. In addition, a variable *Overall safety management level* is included in the model. It consists of two states, *adequate* and *inadequate* and is defined so that if any (or several) of the 23 safety management subarea variables is *poor*, *Overall safety management level* is always in the state *inadequate*. In other words, in order to reach *adequate Overall safety management level*, all safety management subareas are required to be *good* or *average*. As the available computer memory resources do not allow linking all 23 three-state subarea variables directly to the *Overall safety management level* and thus producing a conditional probability table with 3^{23} elements, the subareas are connected through five logical auxiliary variables which do not alter the model behavior.

The links between the network variables are determined with expert opinion. On the basis of a preliminary set of links proposed by the authors, first three maritime safety researchers and then the experts assessing the model parameters (see Section 2.3) evaluate and review the connections.

2.3. Safety management model parameter estimation

The conditional probability tables of the *Safety management* variables are based on expert elicitation. Several experts are used and they are selected so that their combined maritime safety