A Bayesian Network Approach to Assessing the Risk and Reliability of Maritime Transport

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Abstract. The paper presents a conception of a doctoral dissertation, which concerns the problem of estimation of maritime risk and reliability of maritime transport services. In the dissertation a method for dynamic risk assessment based on the Bayesian Network approach is presented. The method concern the risk of an individual ship and its aim is to identify ships, which pose a potential threat due to their individual behaviour and characteristics. Within the article, the following aspects of the dissertation are presented: motivation standing behind the research, main assumptions for the proposed method, its novelty in comparison to existing solutions as well as preliminary results.

1 Introduction

Along with the development of technology, shipping has become an increasingly efficient and swift mode of transport. Nowadays, around 90% of the global trade by volume and 70% by value is carried by sea. As a result, the maritime transport plays nowadays a key role in transporting goods and supply chain management, being the backbone of the international trade and the leader in terms of transport economics. In this context, provision of high reliability of maritime transport is key. The reliability means successful performance of shipment under operating conditions, at a given time and with no damage to a cargo. This, in turn, requires ensuring supply security and risk management.

Taking into account the variety of maritime threats and anomalies, like involvement of ships in illegal activities, maritime accidents, pollution, piracy and terrorism, estimation of the maritime risk and the transport reliability is a crucial aspect. However, there is still a need for appropriate methods and systems, which would allow to assess the risk for an individual ship, taking into account a wide range of possible threats and which would allow to assess risk dynamically and on a continual basis. The existing approaches to the maritime risk assessment do not include all these aspects and focus mainly on a single type of threat and the estimation of risk in the long term.

This paper presents a method for assessment of the maritime risk, by estimating dynamically the risk posed by an individual ship. The method is based on the Bayesian Network and allows to evaluate the reliability of the maritime transport in the short-term horizon. The proposed approach is addressed to various entities from the maritime domain, such as logistics providers and receivers

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of transported cargo, since it is about facilitating the automatic comparison of ships from the point of view of the risk they pose and the reliability of supply.

The structure of the paper includes the motivation for the research (Sect. 2), literature review (Sect. 3), indication of identified gaps, followed by presentation of research objectives and the method (Sect. 4) as well as preliminary research results (Sect. 5). The article concludes with indication of future work.

2 Importance of the Research

With the growing seaborne trade increases the usage of maritime areas. This in turn leads to the rising number of various maritime threats and anomalies, despite existence of a number of maritime codes and conventions, which regulate the security and performance of the maritime transport. The threats encompass a behaviour, deviating from what is usual, normal, expected, or that is not conforming to rules and laws in force, such as illegal activities at sea, pollution, piracy and terrorism as well as a trend to register merchant vessels under the "flag of convenience" and dangerous behaviour of ships (grounding, sudden change of speed, deviation from standard route, close proximity to other objects) [1,2]. As a result, the issues of controlling the maritime traffic, providing security and safety of ships and cargo and ensuring the reliability of maritime transport gain nowadays in importance.

The maritime security is the status of conditions under which a threat to life, health, property and environment does not exceed the acceptable level of risk [3]. The maritime security can be also considered from the point of view of the supply reliability. It is defined as the level of guarantee that the cargo shipped by a vessel will be successfully delivered to a customer (recipient of cargo).

The measure of the supply reliability is a risk (probability of occurrence) of an undesired event (threat), negatively influencing the delivery. This event can be related to human life, ship or environment. This means that the higher risk posed by a ship, the lower reliability of supply. Thus, assessment of the maritime risk is required in order to determine the reliability of maritime transport.

According to the SOLAS convention, ships and ports are obliged to develop individual plans of protection and defence against threats. The plan should include analysis and assessment of risk for various categories of threats and mitigations measures. However, such a plan is developed by the shipowner and is confidential. It means that other entities do not have access to the results of the risk assessment of a particular ship and are forced to assess the risk level on their own.

Taking into account the above-mentioned challenges, the dissertation concerns development of a novel approach to dynamic assessment of risk posed by an individual ship. The proposed method may be helpful for various entities from the maritime domain in conducting a risk analysis and determination of reliability of supply of goods by sea.

3 Literature Review

The research on risk assessment has a long history in other domains, like health, finance, insurance or project management as well as in transport industries (air, rail and military). In various applications different approaches, analytic methods and systems are used, starting from the statistical analysis, through simulation based on historical data, artificial intelligence methods to rule-based systems. Depending on the specific features of the domain, different methods, variables and data are used. In this context, also the risk assessment of the maritime transport requires taking into consideration domain-specific features, such as dynamic changes of sea conditions, types of data (e.g. localization and routes) and the variety of maritime threats.

There exist diverse approaches to the maritime risk analyses (see e.g. [4]). In 2010, shipping companies agreed to use standardized procedures in order to assess risk in key shipboard operations, proposed by the International Maritime Organisation. It is called the Formal Safety Assessment (FSA) [5,6]. FSA process consists of five steps [7]:

1. Identification of all hazards related to an activity or a ship,
2. Risk assessment, consisting in building a risk model and determining probabilities and consequences for all branches of the risk model,
3. Identification of risk control options, which can mitigate the most important risk,
4. Costs/benefits assessment for each option of risk mitigation and preparing a ranking of risk control options,
5. Recommendations for decision making and development of a plan of the activities, if viable.

There are many different analysis techniques and models that have been developed to aid in conducting different FSA steps. Since FSA is relatively new standard, these methods are still under development and testing. Some examples are presented in the following paragraphs[1].

With regard to hazard identification, popular methods are: literature review, brainstorming, interviews with experts, or more formalized methods like HAZOP, FMEA, HAZID [7,8]

The risk assessment concerns mainly building a risk model. From the point of view of information systems, the risk models are developed based on various artificial intelligence and machine learning methods. They focus mainly on modelling a "normal behaviour" of a ships by using supervised and unsupervised techniques, such as classification, SVM, clustering, neural networks, rule-based systems [9–11].

The existing methods can be also divided into qualitative and quantitative. The first includes statistic analysis based on historical data [12], Fault and Event Tree Analysis [6], Bayesian Networks [5], correlation analysis and fuzzy

[1] Since the research focuses only on the first two steps of FSA, only methods for risk identification and assessment are presented.

logic [13,14]. The quantitative methods encompass risk matrices, risk profiles or risk indexes/rankings [8]. The last one can be used to make relative comparison of various objects of the same type when it comes to their attributes (e.g. ship's characteristics).

In this research, utilization of Bayesian Network (BN) is assumed. This approach has some advantages in comparison to other methods, which are important from the point of view og the risk analysis. These are: ability to model cause-effect and casual relations between variables and their probability distribution (inclusion of uncertainty), tolerance for missing data, possibility to include a prior information (expert knowledge) and ability to model changes in time (by using the dynamic BNs). BNs are also easier to validate and evaluate [15]. Moreover, the literature shows that BNs were successfully used in other domains for the risk assessment: ecology [16], natural hazards [17,18], project and enterprise risk management [11] and health [19]. Finally, BN models are more and more used in dependability analyses to support aspects such as reliability, availability and maintainability [20].

4 Research Objectives and Method

The problem of detection of high risk ships, which do not provide high reliability of transport services, is one of the key aspects of international supply chains management. It is crucial for various entities working in the maritime domain (e.g. logistic providers, maritime operators) to effectively assure high quality of logistic services.

The conducted literature review allowed to reveal some shortcomings or disadvantages of the existing methods. Firstly, they focus on estimating risk of either a specified hazard (e.g. collision, oil spill) or an undesired event in relation to ship's technical attributes (e.g. problem with engine) or a human error. As a result, they take into account only selected factors, strictly connected with a given type of hazard. Besides, the estimated risk concerns a particular group of ships (e.g. tankers with the same or similar characteristics) instead of an individual ship.

Secondly, the analysed methods use limited set of factors, like technical characteristics of a ship, experience of the crew, history of accidents. They do not include aspects which may change in time (e.g. flag, owner, classification status), current and historical anomalies in ship's behaviour, past routes and current localization.

Finally, they provide information about the long- or mid-term risk level (especially, when it comes to reliability of supply performed by merchant ships) [21]. The short-term risk, which may change dynamically in time is not included (with exception of the method proposed by Balmat et al. [13]).

Behind the background discussed in the previous sections as well as identified gaps in the area of maritime risk assessment, the author propose a novel Maritime Risk Assessment Method (MRAM) for merchant ships, allowing to dynamically assess level of risk and reliability of supply of an individual ship.

In the following sections the research objectives and main assumptions of the proposed method are presented.

4.1 Research Objectives

The objectives of the research are as follows:

1. To develop a Maritime Risk Assessment Method (MRAM), based on Bayesian Network approach, used for dynamic analysis of risk and reliability of an individual ship.
2. To evaluate the efficiency of the proposed method through set of experiments performed using the real data.

The overall methodology used within the dissertation follows principles devised by the design science [22]. The research is structured into the following steps: state of the art analysis, identification of shortcoming and gaps (problem definition), artifact design in order to fulfil the requirements identified during the problem definition and finally evaluation based on a set of experiments. The research assumes adoption of solutions known in other fields (Bayesian Networks) to new problems (maritime risk analysis). The artifact to be developed and evaluated is MRAM method.

The posed research questions and detailed research goals encompass:

– How to indicate which ships are the most risky with regard to realization of the transport service? Which ships guarantee the highest reliability of goods' supply?
  Goals: determination of quality attributes of transport services realized by sea, definition of the maritime risk and its relation with security of the maritime transport and the reliability of goods' supply.
– How to estimate individual risk level for a ship? What factors and variables determine this risk level?
  Goal: review and selection of quantitative and qualitative methods for the risk assessment and creation of risk classifiers based on real maritime-related data.
– Which factors and variables are significant for the risk assessment?
  Goal: determination of weights for given variables, according to various business scenarios.
– How to estimate risk dynamically (short-term risk) and individually for each ship?
  Goal: proposal of a method for dynamic processing and analysing of maritime-related.
– How to evaluate the proposed method?
  Goals: conduct set of experiments based on real maritime-related data, which would allow to determine the efficiency of MRAM and compare it to other maritime risk assessment approaches.

We hypothesise that utilization of MRAM, which dynamically evaluates individual risk of a ship, will allow to improve the process of discovering and ranking ships from the point of view of the risk they pose and the reliability of goods' supply.

4.2 Research Method

MRAM dynamically calculates the individual risk of a given ship and thus allows to assess the quality and the reliability of the transport service realised by the ship. The method is based on the risk index approach, which consists of four types of risk factors (classifiers): static, dynamic, voyage-related and history-related.

The individual risk index means that the risk is being estimated separately for each ship based on its individual features. The dynamic risk assessment means that the level of risk for each ship may change in time and depends not only on static variables (e.g. age, size), but also dynamic ones (e.g. actual route, position, navigational status). The index is an one-dimensional measure, which indicates the level of reliability of the transport service being realised by a particular ship.

Moreover, MRAM assumes differentiation of critical factors, which more heavily may influence the overall risk. These factors are distinguished by assigning weights to them. This allows to take into account different context and business scenarios in which the method can be used (e.g. the importance of a given factor can be different for different actors/stakeholders).

In MRAM, we limit our discussion to the risk of an undesirable event and define the maritime risk as the probability of occurrence of an undesirable event, or the chance of a loss, which in turn may negatively influence the reliability of supply. This undesirable event may be caused by a ship, due to its individual features and/or behaviour.

In the research we focus only on transport performed by merchant cargo vessels. It includes only ships, which transport cargo for hire, such as general cargo, tankers, bulk carriers, containers.

In comparison to the existing methods for the maritime risk assessment, MRAM provides some advantages. Firstly, it focuses on estimation of the overall risk for a ship, not the risk of an undesirable event or threat related to human error or technical matters. Moreover, it takes into account 4 different types of risk and includes variables, which have not been yet used to estimate the maritime risk, such as past anomalies, classification status, detentions and bans, etc. Finally, the proposed method calculates the risk dynamically, what allows to determine the reliability of supply in the short-term horizon and individually for each ship.

The proposed approach is a flexible solution, which may be utilized by various entities from the maritime domain. Firstly, MRAM can provide information about the ships with the low supply reliability. Here interested entities are logistic companies, senders and recipients of goods, ship owners/managers, etc. Besides, the results may indicate ships which require special attention due to safety and security reasons. Here potential users are port authorities (maritime offices, custom services, SAR, etc.) and state authorities (in order to control the supply of key resources like gas or oil). The aim of MRAM is to support users in making decisions and may be incorporated into the existing maritime and logistic systems for monitoring fleet or maritime traffic as well as in intelligent navigational systems.

5 Preliminary Results

In this section the results of the already conducted work on the proposed method is presented. It encompasses identification of risk factors, selection of data sources, determination of statical variables significant for the risk estimation and proposal of models for the static risk classifier.

5.1 Risk Factors and Risk Assessment

The risk for a ship may depend on various factors and variables, which altogether determine the overall risk level (risk index). In the proposed method these variables were divided into 4 risk factors (Table 1).

Table 1. Risk factors

Name	Description	Variables
Static	Static attributes of a ship, which do not change at all or change very rare	Size, flag, age, type, classification society, classification status
Voyage-related	Variables connected with a current voyage of a ship	Crew, type of cargo, departure and destination port/country
Dynamic	Variables that change during the voyage as well as anomalies in ship's behaviour	Weather conditions, incomplete AIS messages, deviations from standard routes, change of static parameters, ambiguous identification, loitering at high sea
History-related	Historical information about a ship and detected past anomalies	Past detentions, accidents, visited ports, port state controls

Moreover it is assumed that each risk factor and each variable has a different weight assigned. The weights may change for different maritime scenarios/contexts and reflect the significance of a given factor for a given stakeholder in a given context.

Table 1 and Fig. 1 presents examples of variables, which may be taken into account in MRAM for calculation of the overall risk. Each of these variables can have a positive or a negative influence on the risk level. This influence may be estimated based on analytical methods (quantitative approach) or opinion and knowledge of experts (qualitative approach). The quantitative approach encompasses such analyses methods as correlation, regression, building classifiers or rankings [23], which provide information about significance of a given variable in the further reasoning and the assessment of risk. The qualitative approach includes a fuzzy logic and if-then rules techniques [14]. In order to connect results of both approaches, Bayesian Networks (BN) are used, which allows to include both deterministic and probabilistic information.

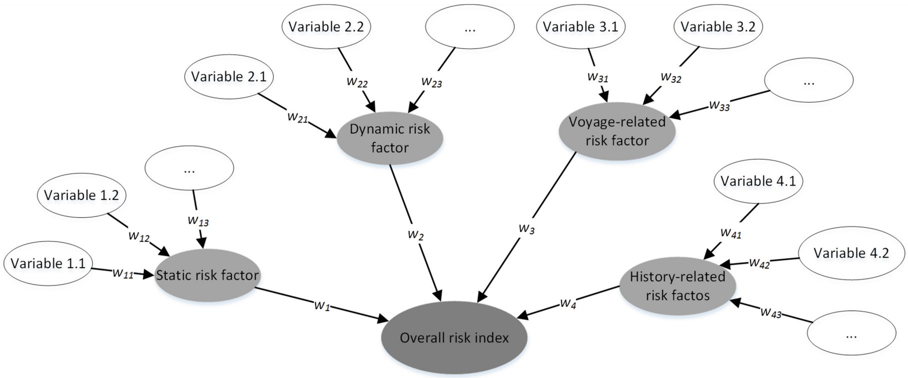

Fig. 1. The risk factors and the overall risk index

In the proposed method, BN allows to model the structure of variables which influence a given risk factor and based on that estimate the risk level. Knowing the value of the overall risk index it is then possible to rank the ships according the risk they pose (the reliability of supply).

5.2 Data Sources

In order to assess the maritime risk, various data may be used. The author has already analysed and selected data sources, which are going to be used to perform the evaluation of MRAM and to determine variables which should be taken into account in the risk calculation.

The first data source is Automatic Identification System (AIS). AIS is an automatic tracking system used for identifying and locating vessels in real time. It is based on automatic exchange of data about a ship and its movement with other nearby ships, AIS base stations and satellites. It includes navigational data (location, course, speed, navigational status), static data (identification numbers, type, name, callsign) and voyage data (destination port, estimated time of arrival). Nowadays, AIS is used as one of the main data source in the maritime surveillance.

Another group of data sources are open Internet databases (open data published in various maritime-related Internet sources). They encompass data about ship's accidents (GISIS database[2]), detentions and inspections of ships (databases of Tokyo[3], Indian Ocean[4], Mediterranean[5] and Black Sea[6] MoU's and US

[2] https://gisis.imo.org.
[3] http://www.tokyo-mou.org/.
[4] http://www.iomou.org/.
[5] http://www.medmou.org/.
[6] http://www.bsmou.org/.

Coast Guard[7]), ships characteristics (data available at MarineTraffic[8], Maritime-Connector[9] and ITU MARS[10]) and classification of ships (IACS database and reports[11]).

The data from the selected sources has already been retrieved during the work on the related project SIMMO.

5.3 Selection of Variables for Static Classifier

After definition of MRAM's assumptions and selection of data sources, the further work concerned assessment and selection of variables for the proposed risk classifiers. In the first instance, the analyses were focused on variables for the static factor. The analysed variables included: ship's age, size, type, flag, classification society and classification status.

In order to determine, which of the static variables are significant for the risk determination, three types of analyses were conducted: correlation, logistic regression and finally building of BN.

In the conducted analyses, apart from the data about ships retrieved from the data sources listed in the previous paragraph, also data on maritime accidents from the GISIS database was used. It was assumed that if a ship took part in an accident, the risk level for this ship is higher than for ships that never caused any accident. The size of the sample was 466 accidents, including 533 ships (accidental ships), which have happened in the period 01.01.2014-15.03.2016. Besides, for some of the conducted analyses also the data about non-accidental ships was included.

Firstly, it was analysed what is the relation between the static attributes (flag, classification society, classification status, type, size and age) and the accident rate. Based on that the following results were obtained:

– *flag* - a list of flags with the highest accident rate and weights for different flags, saying how risky the ships flying a given flag are, taking into account the accident rate,
– *classification society* - selection of unreliable classification societies (with regard to the accident rate),
– *classification status* - selection of classification statuses, which may influence the accident rate; almost one third of the ships with accident history had *suspended* or *withdrawn* status, when accident happened; both statuses indicate that the accidental ships did not meet all safety-related requirements and standards, what may have contributed to the accident,
– *type* - a list of the most dangerous ship types,

[7] http://cgmix.uscg.mil/PSIX/PSIXSearch.aspx.
[8] https://www.marinetraffic.com.
[9] http://maritime-connector.com.
[10] http://www.itu.int/en/ITU-R/terrestrial/mars/Pages/MARS.aspx.
[11] http://www.iacs.org.uk/shipdata.

– *size* - a distribution of ship's size among the accidental ships; result: mostly small ships (below 500GT) cause the accidents,
– *age* - a distribution of ship's age among the accidental ships; result: mostly young ships (below 5 years) cause the accidents;

Then, the correlation analysis between the accident rate and the ship's age and flag using 3 correlation coefficients was performed[12]. The obtained results show that there is a moderate positive relation between flag and accident rate. It means that along with the increase of the number of ships flying a given flag, increases the accident rate. Correlation between the accident rate and the age is moderate and negative, which means that with the age, the number of accidents decreases. The calculated coefficients can be used as a weights for particular variables.

In the next step, the regression analysis was performed and two logistic regression models were developed (using the Bayesian generalized linear model). The models allow to determine the probability of an accident based on the static attributes of a ship. The main difference between the models is that the first takes the original distribution of all variables, while the second takes the linearised quantitative variables (age, size)[13]. Nevertheless, evaluation of the models showed that both can be used as the static risk classifiers, however only two variables (age and type) are significant.

Finally, in order to determine relations between all the analysed static variables, a model of Bayesian Network was developed. The model shows the cause-effect relationships between variables and provides probability distribution of the static attributes. It can be used to estimate the probability of making an accident by a particular ship, knowing its static attributes.

The structure of the BN was learnt, based on the real data about ships and accidents, using the method proposed by [24]. To determine the best version of the BN, a set of experiments were performed, in which various versions of BN were analysed and compared. In this process also results and constraints from the previous analyses (correlation and regression) were taken into account. Based on the log marginal likelihood measure, the model of BN best fitted to the empirical data was then selected (Fig. 2). The model shows that the significant variables for assessment of risk for the static classifier are: age, type, classification status (suspended and withdrawn).

To sum up, the paper presents the assumptions and results of work conducted on the Maritime Risk Assessment Method. The research so far concerned the definition of the maritime factors and variables, the selection of data sources as well as the analyses of variables for the estimation of the static risk factor. Future

[12] Correlation analysis was limited to quantitative variables only (age and number of ships flying a given flag). It results from the assumptions to use the following coefficients: Pearson, Kendall and Spearman. Besides, the existence of correlation between ship's size and accident rate was confirmed using the nCochran-Mantek-Haenschel and Fisher tests.

[13] The distribution of original quantitative variables (age and size) is not linear what may influence the results of model's calculations.

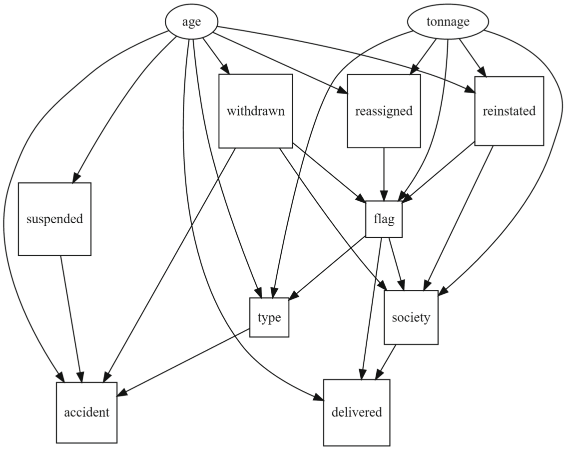

Fig. 2. Model of Bayesian Network for static risk factor

work on will concern further verification of the developed models for the static risk estimation, determination of models for the three remaining risk factors and the overall risk index, and finally evaluation of the whole method. Moreover, consultation with the maritime experts is envisioned in order to ensure that results of MRAM meet their requirements and needs.

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