Bayesian networks as a decision making tool to plan and assess maritime safety management indicators.

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Abstract: Today, maritime safety management norms, self-assessment guides and frameworks demand and/or recommend the collection, report, and analysis of indicators to measure the safety performance of shipping companies. However, the characteristic of classic indicators only provide information about the specific evaluated activity. In this paper, a new quantitative and qualitative option to jointly analyze the performance of individual and collective indicators of a maritime safety management system is proposed. For this purpose, the dependencies between the quality of the most representative components of maritime safety management and their designated indicators levels are probabilistically estimated using a Bayesian network model and two expert views. Each component has one or more designated indicators which aim to identify practical values for the performance of those components. Based on the findings of this study, the implementation of the Bayesian network model seem to provide a unique decision support tool to plan and set indicators, and also to evaluate the indicators' performance and the effect on their designated components. Furthermore, the use of the indicators in the model enable detecting their repercussion on other components of an evaluated safety management system, even when those components do not seem to be directly related.

Keywords: Maritime safety management, Safety management systems, Indicators, Bayesian networks.

1. INTRODUCTION

There are several definitions regarding to the concept of Key Performance Indicators (KPIs), these definitions vary according to the field of indicators' application (e.g. financial, management business, operational). From a general and simple perspective, indicators are quantitatively and/or qualitatively references used to measure how processes perform to obtain planned goals [1]. In maritime safety management, indicators are described as discrete measures which track organization's effectiveness in meeting its aims and objectives [2].

Commonly, KPIs have four defined phases before, during, and after assessing the performance level of certain activity. These phases are related with the initial step of clearly defining the indicator with an accurate setting of the aim of the indicator and target values. A second phase includes the continual monitoring of the indicator, even when there is no need to report it. Then, a third phase is performed for collecting and reporting the indicator. And finally, a phase for a posterior development of actions based on the information reported [3]. In the maritime industry, shipping companies have established safety management systems (SMS) which constantly need to be evaluated in order to evidence if companies are gradually obtaining their planned safety performance. Furthermore, the mentioned evaluations may also evidence if the safety management planning phase is being realistic [3].

The setting of safety management indicators is normally supported by the integration of expert knowledge, the evaluation of organization's available resources, and the available company's historical data of each analyzed safety management aspect (see section 2.1). The monitoring and reporting of the established indicators constantly demand an analysis of the current situation in a performed activity [4]. However, this traditional process of monitoring and reporting indicators allow only analyzing the indicator's influence on a single evaluated component of a safety management system (SMS), without evidencing its affectation in some other different components. In this paper, a new proposal to plan, monitor, and evaluate maritime safety management indicators through the implementation of Bayesian networks is provided. The aim is to quantitatively analyze the performance of the main components of the SMSs in two different shipping companies based on the experts' estimations on practical indicators of those components. The properties of the resulting model is then demonstrated with a hypothetical evidence which could have been derived from periodic reports of a shipping company's SMS.

The paper is organized as follows. Section 2 describes the different material and methods utilized in this study. The main results and findings are presented in Section 3. The section 4 discusses the results further. And finally, conclusions are drawn in Section 5.

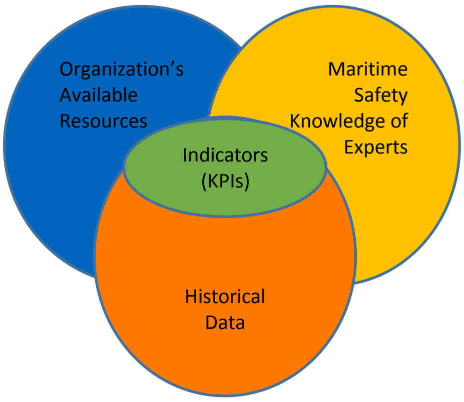
2. MATERIAL AND METHODS

2.1. Maritime safety management indicators framework

Today, a common organizational approach when setting, monitoring and evaluating indicators is composed of three key features. The first one is the knowledge of the experts regarding the analyzed safety management area and/or component. This knowledge includes adapting the indicators to the safety management strategy, targets and priorities of the organization, and also the expert knowledge regarding the experience of previous performance of the area/component analyzed by the indicator [5]. The second feature is the designated resources to manage the area evaluated by the indicator, including monetary aspects and the available personnel and technology [6]. The last feature includes the utilization of all available historical data which provide evidence on previous performance of the safety management component or area analyzed by the indicator [7]. Figure 1 present a general perspective of the mentioned components utilized for setting key performance.

In this research, the proposed framework and its key features have been used as an initial guidance for the consulted experts regarding the main aspects to consider when selecting their personal estimation of the presented indicators.

Figure 1. Key features on the setting, monitoring and evaluating of indicators



2.2. Bayesian networks

Bayesian networks (BNs) is a technique that can depict relatively complex, possibly but not necessarily causal dependencies and confront with uncertain and unobserved variables while also having a graphical volume [8]. Basically, a BN is a graphical model that encodes probabilistic relationships among variables of interest [9]. Each variable consists of a finite number of mutually exclusive states. And each state has a probability of event and it may also depends on the states of the variable's parent nodes, i.e., the variables with a straight link to the variable under analysis. The utilization of Bayesian networks have become more popular in the last twenty years because their application has been benefited from the development of new computational algorithms and software tools [10]. In the maritime domain, Bayesian networks have already been applied in several maritime traffic safety related models for accident analysis, accidents occurrence estimations, and vessels' potential oil spills e.g. [11; 12; 13; 14; 15; 16]. In this paper, the dependencies between safety management indicators and SMS components are also modeled with BNs. The probability distributions of these safety management indicators are modeled with triangular distributions, whose parameters (min, max, and mode) are based on expert opinion. The constitution of the analysis of indicators presented in this study is explained more in details in the following subsections.

2.3. Analyzing safety management indicators through Bayesian networks

2.3.1 The Safety management model.

The structure and components of maritime safety management utilized in this study are based in the components of maritime safety management proposed in [17], and a Bayesian network model of maritime safety management proposed in [18]. In those studies, 23 components of maritime safety management were extracted from the contents of three documents including maritime safety regulations and frameworks: the International Safety Management (ISM) Code [19], the Tanker Management Self-Assessment (TMSA) [21], and the analysis of the safety management framework proposed in [21]. The 23 components are: 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, 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, and training. All these variables were allocated within a Bayesian network model of maritime safety management (see [19]), and three mutually exclusive states (good, average, and poor) were designated to each variable. The links between the network variables were determined with expert opinion.

The conditional probability tables of the safety management variables are based on expert elicitation. Two Safety Designated Persons Ashore (DPAs) in two different shipping companies have contributed in this task:

- Expert 1: A safety DPA of a Finnish shipping company operating ro-ro and ro-pax vessels and providing port operations.
- Expert 2: A safety DPA of a Finnish shipping company operating ro-ro vessels and general cargo ships.

2.3.2 The estimation of the indicators' values

53 indicators extracted and proposed in [18], were allocated to each safety management variable, having components with a minimum of 1 indicator and maximum of 7 indicators. Table 1 contains an example of 10 indicators designated to the maritime safety management variables. For the indicators' estimation by the experts, a structured questionnaire was implemented in order to extract numerical indicators given each of the three mutually exclusive states of the parent variables. In this questionnaire, the experts had to assess the parameters of the triangular distribution of all the indicators. Thus, for each safety management variable the experts were required to provide three values per three established states (poor, average, and good) of the analyzed variable, providing a total of 477 values. These values should provide the minimum, maximum and mode number or percentage of every indicator. Table 2 presents a simple example of the questions proposed to the experts.

Table 1: An example of indicators designated to some of the maritime safety management variables

Variable	Indicators
Communication	Average grade on the annual internal communication evaluation (e.g. from staff satisfaction survey)
Ship operations	Number of blackouts reported by ships per year Number of fires reported during ships operations per year Number of navigational errors reported in a year? Percentage of the ships reaching destination on time (plan vs. real) Safety Percentage of the ships reaching destination on time (plan vs. real) technical
Maintenance	Total out of service time due to a failure in the Maintenance Management System.
IT SM system	Percentage of organization's personnel satisfied with the IT SM System
Acc. and Inc. rep.	Number of accidents reported per year?
Training	Average grade on the internal training provided to the organization's staff?

Table 2: An example of the utilized questionnaire in the experts' estimation of the indicators

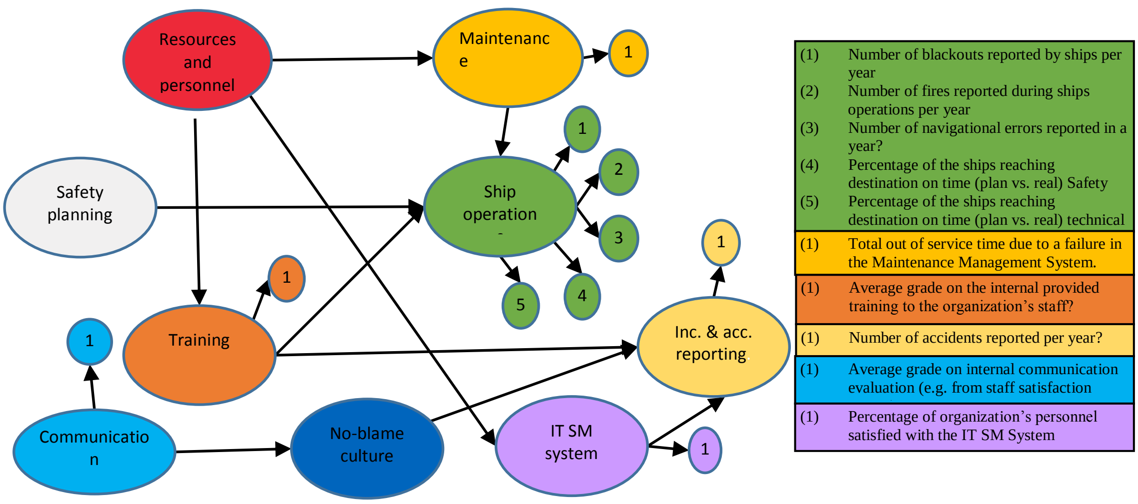
Element	Indicator	Amount that represents:	Max	Mod	Min
Ship operations	Number of blackouts reported by ships per year	Good ship operations	3	2	0
		Average ship operations	7	5	3
		Poor ship operations	15	12	7

3. RESULTS

3.1 The network model

Figure 2 presents an extract from the model, showing the network structure with some of the safety management variables (based on [19] and their respective indicators.

Figure 2: A Bayesian network with safety management variables and their indicators



The conditional probability distributions of the safety management variables presented in the Figure 2 have been adopted from [19].

3.2 The estimated indicators

Table 3 presents some of the estimated indicators by the experts. At this point, it is important to remember that such estimations are based on the components introduced in Section 2.1. Thus, the estimations are provided by two experts from two different organizations with different: strategies, objectives, resources and organizational structure.

Table 3: Experts' estimation of the indicators

Element	Indicator	State	Expert 1			Expert 2		
			Max	Mod	Min	Max	Mod	Min
Ship operations	Number of blackouts reported by ships per year	Good	0	3	5	0	0	0
		Average	6	10	15	1	1	1
		Poor	15	25	35	1	1	1
	Number of fires reported during ships operations per year	Good	0	2	4	0	0	0
		Average	5	7	10	0	0	0
		Poor	11	15	20	1	1	1
	Number of navigational errors reported in a year?	Good	0	3	5	3	2	0
		Average	6	10	15	5	4	4
		Poor	15	25	35	10	7	6
	Percentage of the ships reaching destination on time (plan vs. real) Safety	Good	100	92	90	100	97	95
		Average	90	85	80	94	87	80
		Poor	80	75	70	79	67	50
	Percentage of the ships reaching destination on time (plan vs. real) technical	Good	100	99	97	100	100	100
		Average	96	94	92	99	98	98
		Poor	92	90	88	97	90	80
Training	Average grade on the internal provided training to the organization's staff?	Good	5	4	4	5	4.5	4
		Average	4	3.5	3	4	3	3
		Poor	2.5	2	1	2.9	2	2
Maintenance	Total out of service time (in days) due to a failure in the Maintenance Management System.	Good	2	1	0	2	1	0
		Average	7	5	3	5	4	3
		Poor	15	11	8	15	9	6
Communication	Average grade on internal communication evaluation (e.g. from staff satisfaction survey)	Good	5	4.2	4	5	4.5	4
		Average	4	3	2	4	3.5	3.5
		Poor	2	1	0	3	2.5	2
Accident & incident reporting and analysing	Number of accidents reported per year?	Good	2	1	0	0	0	0
		Average	15	7	3	5	3	1
		Poor	30	23	16	10	7	6

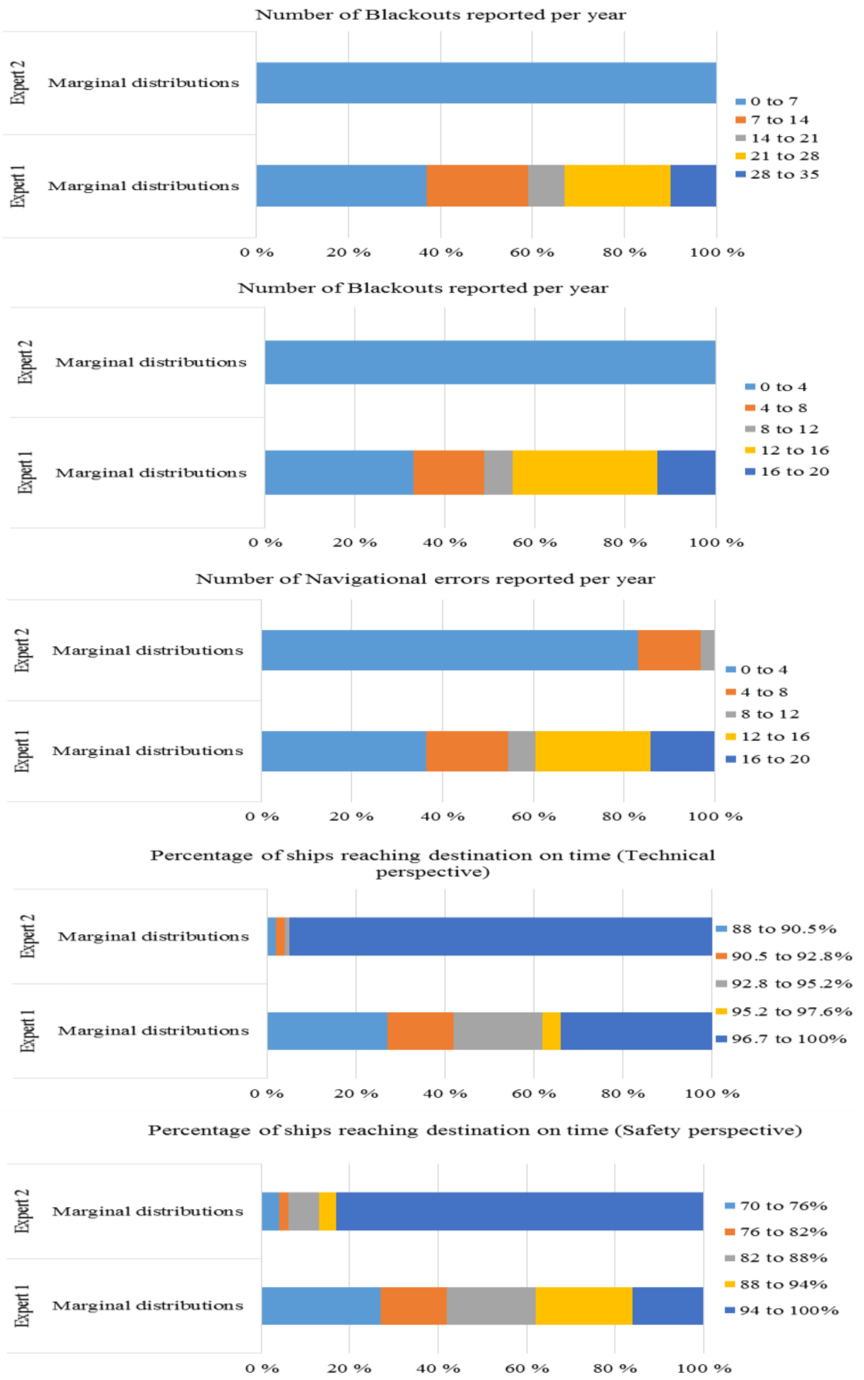
The resulting model can be used in evaluating the indicative properties of the chosen indicators not only for its parent variable, that is, the safety management component to be estimated through the indicator in question, but also for the other safety management components and their indicators.

3.3 Indicators in action

3.3.1 Clear specified values and "targets"

Figure 3 graphically presents the marginal distributions for the indicators of the component ship operations. In this figure, the experts are able to visualize the different values for each state of the practical measured area and component based on their probability estimations of these components, and the designated values for the indicators. In the figure, the same scale is utilized in order to compare how different values can be represented in the indicators according to the needs, targets, and general structure of the companies.

Figure 3: Marginal distributions of the indicators for the component “ship operations”



3.3.2 Hypothetical scenarios

Figure 4-5 presents the functioning of the Bayesian network when evidence is available for some of the indicators. In the hypothetical example of Figure 5, the shipping company 1 has had 3 navigational errors reported, 2 blackouts experienced, 0 fires reported, and 92% of ships reaching destination on time. The status observed in the component ship operations are: 1% probability of having good ship operations, 99% probability of having average ship operations and 0% probability of having poor ship operations. And for the expert 2 (Figure 5), having 1 navigational error reported, 0 blackouts experienced, 0 fires suffered, and the 99.2% of ships reaching destination on time, represents: 100% probability of having good ship operations.

Figure 4. Introducing the real data of the indicators of ship operations (Expert 1)

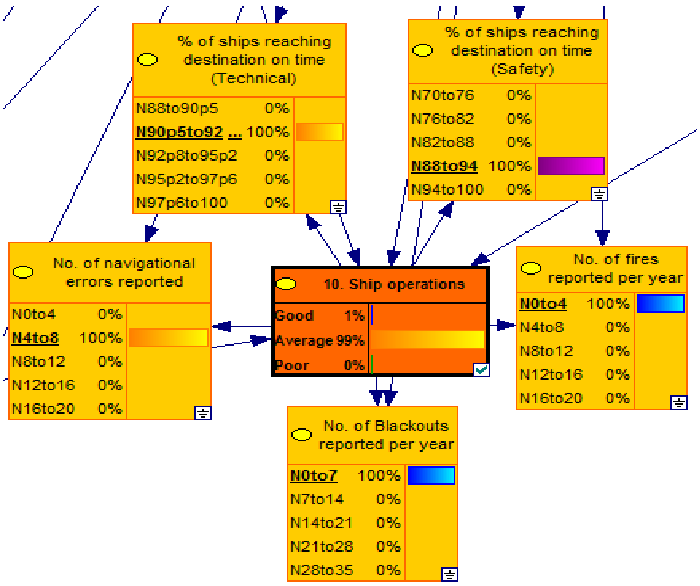


Figure 5. Introducing the real data of the indicators of ship operations (Expert 2)

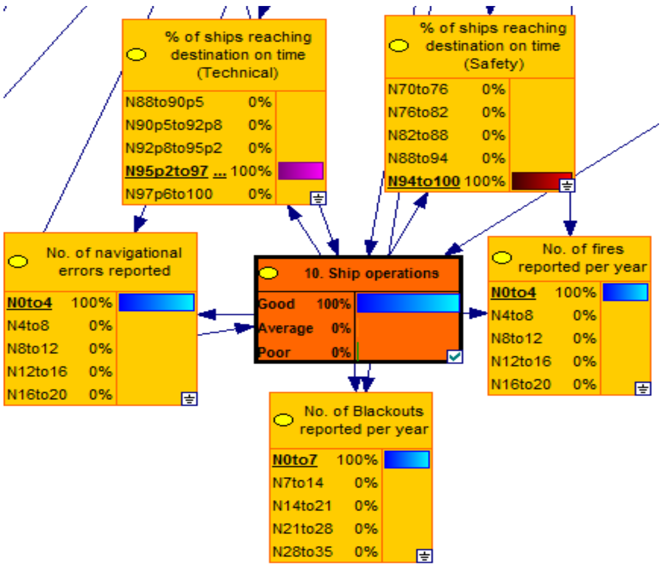
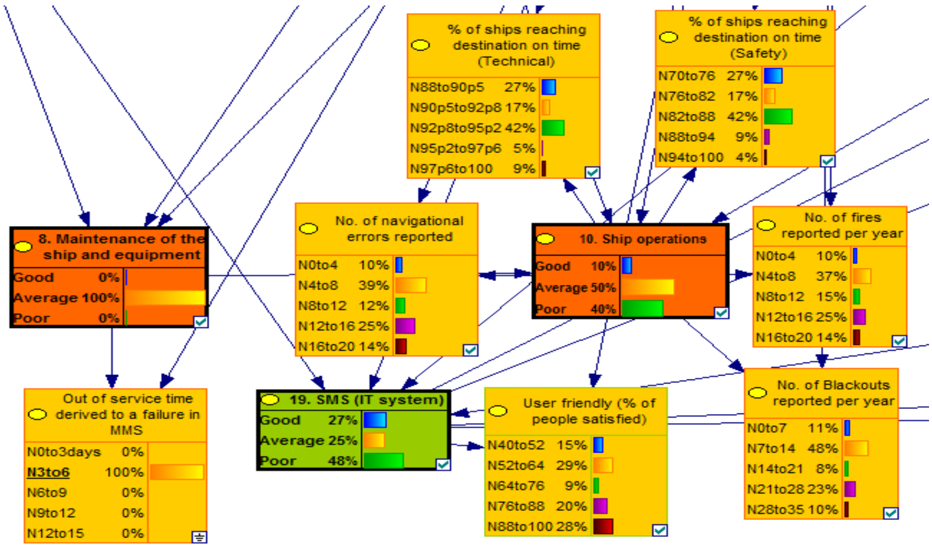


Figure 6 presents the effects of hypothetical knowledge on 5 reported days of out of service time in the fleet and/or machinery belonging to the organization of expert 1. Thus, this amount of service time directly represents 100% probability of having average maintenance of the ship and equipment. However, observing this indicator value has also updated the knowledge on other variables, and also on the other indicators. For example, this observation has updated the variable ship operations to 10, 50 and 40% probabilities of having good, average and poor ship operations respectively. The status of the IT SM system has also been updated by this hypothetical, the component presents: 27, 25 and 48% probabilities of having a good, average and poor levels, respectively. Furthermore, the observed probabilities in other indicators have also been also affected by the inclusion of the mentioned observation. For example, the observation of the mentioned indicator yields a 10% probability of having reported 0 to 4 navigational errors per year, 11 % of having reported 0 to 7 blackouts yearly, and 9% probability of having 97 to 100% of the vessels reaching destination on time (from a technical perspective).

Figure 6. The influence of one indicator on its parent variable, and other network variables and indicators.



4. DISCUSSION

The implementation of Bayesian networks to set and assess key performance indicators seen to provide a feasible methodology option to set the adequate amounts to all the state values of the maritime safety management components and its indicators based on company's budgets, strategies and objectives, the knowledge of the experts, and data collected from past experiences. The network structure and the designated probability estimations of those variables have represented the initial step to consider the current situation of the SMS installed within experts' organization. The incorporation of the complementing methodology presented in this paper has attempted to provide an adequate initial approach to set the respective practical values of the components' indicators. By implementing a triangular distribution in the estimation of the indicator's values, the experts have had the opportunity to designate specific amounts to the different states included in the indicators. These amounts provided to each indicators seen to follow a linear scale where the values designated to the states good, average and poor are not commonly overlapped. Thus, this seem to reflect that experts have a clear idea of what can be tolerated as good or average levels and what can be not. Figures 3 presented the marginal distributions of the indicators designated to one safety management component based on the knowledge of two experts from different shipping companies. Through this figure, the experts can visualize the actual numerical values of each indicator based on their previous probability estimation for the components contained within the utilized network model.

The hypothetical scenarios attempt to represent how a real assessment of the indicator can be implemented when comparing actual obtained information (e.g. generated from periodic reports of the SMS) against the estimated during the planning and setting phase. Figures 5 and 6 present the effect of including hypothetical data as an observation in the indicators designated to the variables. Thus, including "actual information" can provided numerical estimations of the states in the analyzed variable, which automatically represent an indicator of the current status of safety management component (in this case: ship operations). This option of including data can be exploded e.g. during the assessment of the complete SMS, and/or any individual components of the system.

The advantage provided by the adopted Bayesian network to complete the process of establishing and assessing key performance indicators is clearly reflected in the results provided in Figure 6. Having an assessed structure of the components integrated within maritime safety management, provided the opportunity of identifying affectations in also different variables and/or indicators which do not necessary need to be directly related to the indicator in which data is included. This effect enable detecting the possible effect of indicator(s) on the complete SMS, and of course, its effect on a single component of the system. Thus, using Bayesian networks for the mentioned purpose provided a new method to analyze the performance of a specific and/or several components of maritime safety management, and their repercussion in different areas. This particular aspect represents a differentiate advantage to jump from the classical methods to establish and assess key performance indicators, to a new method to jointly analyze indicators and the general performance of a SMS.

The resulted inclusion of the indicators on each maritime safety management component included in the original "BN model of safety management" [11] could present unlimited number of different types of queries on the current state of the maritime safety management. Unfortunately, this paper cannot present the results to all possible queries due to the limited amount of information allowed to present here. For this reason, any query regarding this proposal can be provided to some extent by contacting the authors of this paper.

5. CONCLUSIONS

This study has presented how Bayesian networks can be implemented to set and assess maritime safety management indicators. The adopted Bayesian network model of maritime safety management proposed by [11] have represented the initial step where experts have considered the current status of their SMS, and the influence among all the variables. With the inclusion of the indicators to each variable, the two consulted experts were able to represent an example of how organizations with different characteristics may follow a similar process to accurately plan, set and evaluate safety management indicators. The work produce from this research provided the opportunity to analyze the management of safety within one shipping company, or also for comparing targets and results from companies with similar characteristics or characteristics of any particular interest.

The results presented in this paper represent how two different organizations may set and evaluate maritime safety management indicators. The main outcome of this research and its results is represented by the option of having a new methodology which allow not only establishing and evaluating key performance indicators in a traditional way, but also to detect affectations derived from the performance of a specific indicator belonging to a single safety management component on any other component and indicator integrated in the network. It can be concluded that while there is still room for improvement and further validation of the methodology proposed, the option presented here seems to adequately represent several planned targets for performance of different areas or components of maritime safety management which can be easily serve as a starting point for building a detailed maritime safety management decision support tool.

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