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A Ship Safe Speed Identifying Method from Risk Perspectives in Arctic Waters

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Abstract: Increasingly melting of sea ice in the Arctic makes it possible for merchant ships with or without ice class to sail along the North Sea Routes, in particular during the summer seasons. However, ships sailing in the Arctic may still encounter thick (brash or level) ice in certain areas. It can challenge a ship's sailing safety. For safety concern, the ship speed selection is recognized as one of the leading challenges for the operators in the Arctic area. To figure out safe speed selection problem, the two most common accident scenarios- ice stuck and ship-ice collision have been analyzed. Through installing this risk analysis model, the safe speed under various ice conditions can be identified and the relevant results can provide beneficial information on speed selection for Arctic ships.

Keywords: Arctic Navigation, Safe Speed, Quantitative Risk Analysis, Bayesian network.

1. Introduction

With global warming, resulting in the melting of the sea ice in the Arctic, the North Sea Route (NSR) has been put in shipping companies' option lists. However, they still remain cautious about choosing the NSR because of safety concern from sailing in the Arctic ice conditions. From previous literatures and accident reports, ice stuck and ship-ice collision are identified as the most common accident scenarios for ice-going ships. These two accident scenarios when sailing in the Arctic ice areas are affected by the detailed ice conditions and a ship's speed

(McCallum et al., 1996).

The accident scenario of ice stuck is caused due to the loss of a ship's maneuverability in the encountering ice area. Such ice stuck accident scenario has been discussed by many researchers. For example, Montewka et al. (2015) presented two probabilistic models using the Bayesian method to demonstrate the relationship between a ship's performance and her encountered ice conditions. One of the models focused on causation of ship performance with various environmental factors, such as ice conditions and wind speed, while the other models focused on how environmental factors and ship performance will affect the probability of ice stuck events. However, in this research, the engine power is

assumed to be constant as full power and the change of ship speed is only due to encountered ice conditions. It is not realistic for actual Arctic navigation. Fu et al. (2016) introduced a quantitative risk model to estimate the probability of ship ice stuck events. The risk analysis model integrated ship performance data with experts' consultation to construct conditional probability tables (CPTs), which are treated as a vital part of the quantitative Bayesian network model.

Many researchers are also devoted to investigating the risk associated with ship-ice collision scenarios. Khan et al. (2018) developed a dynamic ship-ice collision risk prediction model based on Object-Oriented Bayesian Network. The potential output of the accident was also estimated. In addition, modeling from the mechanism of ship-ice collision can also be used to describe/model the collision risk. Obisesan and Sriramula (2018) firstly proposed performance characterization to estimate the probability of structural damage under ship and iceberg collision. And then the risk of ship-iceberg collision was assessed by developing a Fault Tree (FT) model.

Ship speed is recognized as a joint effect of ice conditions and the thruster. Montewka et al. (2015) initially process the ship AIS (Automatic Identification System) data to match the ice prediction data from ice model HELMI. Then a Bayesian network was proposed to identify the ship speed under diverse situations. Kim et al. (2018) performed an ice tank experiment to find the attainable speed at pack ice condition. The relationship between a ship's speed and other factors such as ice concentration, ice thickness, power, etc. has been modeled using empirical formulas and experiment data.

Although the factors contributing to ice stuck and ship-ice collision may be similar, the mechanism is completely different. For ships sailing in high speed, it is more easily to collide with ice, causing hull damage. Conversely, if a ship navigates with a relatively low speed, she may face a higher risk of stuck in ice. Thus, selecting an appropriate speed under various ice conditions is critical for safe ship navigation in the Arctic. In this study, these two different accident scenarios are integrated into one risk analysis model and the safe speed can be obtained using this risk analysis model.

2 Methodology and Data

2.1 Bayesian Network

Bayesian Network (BN) is a type of probabilistic graphical based Model, which can be used to describe knowledge uncertainty from objective data and expert judgments. BN is widely used in risk assessment related field. A BN is a Direct Acyclic Graph (DAG) that is made up of nodes and edges. Each node of the BN is a random variable. Edges represent probabilistic links between these nodes. These links can imply the conditional dependency between two variables. Moreover, if such a link does not exist between two nodes directly, they may be independent or connected through other nodes indirectly. The

direction of an arc can represent the parent-child relation, with an arrowhead always pointing to a child node.

Every node contains a conditional probability table (CPT), which can imply the probability of the variable given its parent node. A CPT can describe all the conditional probabilities for all the possible combinations of the states of the parent variables. Also, for root nodes with no parent node, the CPT contains prior probabilities of these variables.

The theoretical basis of the Bayesian Network is the Bayes theory, which is shown as follows:

$$P(A|E) = \frac{P(A, E)}{P(E)} = \frac{P(E|A)P(A)}{P(E)} \quad (1)$$

Where $P(A, E)$ is the joint probability of event A and event E . $P(A|E)$ denotes the posterior occurrence probability of A given an evidence E . $P(A)$ represents the prior occurrence probability of A , while $P(E)$ is the marginal occurrence probability of evidence E . $P(E|A)$ is the conditional probability of E given that A occurs. The prior occurrence probability $P(A)$ can be calculated by marginalization, utilizing following equation:

$$P(A) = \sum_E P(A, E) \quad (2)$$

The BN enables the updating of probability distribution over the possible values of each node when more information or evidence becomes available. Such as, when entering evidence E , this evidence or information will propagate through the network altering the joint posterior probabilities of event A as follows:

$$P(A_i|E) = \frac{P(E|A_i)P(A_i)}{\sum_j P(E|A_j)P(A_j)} \quad (3)$$

Entering evidence into the network is a significant part of a probabilistic model. It allows to alter the probabilistic model to a new situation which contains new posterior probability distributions.

2.2 Data Source

The data utilized to construct BN is from three sources: voyage log data recorded by crews, expert opinions and literatures. The 179 rows of voyage log data collected from Yong Sheng contains data of both ship performance and navigation environment. Data about ship performance incorporates ship speed and engine power. While, environmental data refers to general environmental data such as wind speed and wave height, and ice condition data, namely ice concentration and thickness. The part of data used in constructing the current model is shown as Fig. 1. In the presented data, the ice concentration data was retrieved by analyzing the forecast ice conditions given daily by NMEFC (National Marine Environmental Forecasting Center) and observation by crews on board. Meanwhile, the data of wave condition was

recorded as meteorological degree which referred to the Douglas Sea scale (Douglas, 1991). While, the data about ship speed during the voyage was retrieved from the Automatic Information System (AIS). moreover, experts' opinions and information from literatures can help to construct the CPTs.

Fig. 1. Data collected from Yong Sheng

3 Risk Model Analysis

To quantify the risk, a Bayesian network model has been developed using the data described in section 2.2 and experts' opinions. In this section, the details about the nodes selection, model structure and CPTs estimation of current Bayesian model are proposed.

3.1 Nodes selection

The initial work of Bayesian network modeling is to select nodes by identified risk influencing factors from literatures and experts' consultation. To demonstrate risk influencing factors of both ice stuck and ship-ice collision, information from these two fields has been integrated. After identifying all the factors or nodes, these nodes are discretized into various states, which are also derived from experts' views and relevant research, as shown in Table 1.

Table 1. The nodes in BN and their states

Node	State 1	State 2	State 3	State 4
Ice concentration	< 50%	50% ~ 70%	> 70%	
Ice thickness (cm)	< 40	40 ~ 80	> 80	
Speed(kn)	<5	5 ~ 8	8 ~ 11	>11
Power (kW)	< 4500	4500~ 6000	> 6000	
Wave height (m)	< 0.5	0.5 ~ 1.25	> 1.25	
Wind speed (m/s)	< 5.5	5.5 ~ 7.9	> 7.9	
Ice stuck	yes	no		

Ship-ice collision	yes	no		
Ice stuck				
consequence	minor	major	critical	
Ship-ice collision				
consequence	minor	major	critical	

3.2 Model construction

The identified risk factors can be classified as root causes, intermediate causes and immediate causes. In the Bayesian network, those factors are connected by arcs according to the relationship among them. As mentioned in the last section, the considered ship performance factors are engine power and ship speed, while environmental factors are wave, wind, ice concentration and ice thickness. In the current paper, it is assumed that wave and wind conditions only affect ice concentration due to ice drifting. Their effect on ship performance is hypothesized to be omitted (Qian et al., 2016). Thus, the node "ice concentration" is set to be the only child node of the node "wind and wave effect".

Ship speed in ice-covered waters is the product of propulsion and resistance in the ice conditions. The propulsion can be described by the engine power, while resistance can be calculated by empirical formulations. Moreover, ship speed can be altered by adjusting engine power under various ice conditions. Thus, the node "ship speed" is the child node for "ice thickness", "ice concentration" and "engine power". As mentioned before, the nodes of both accident types, ice stuck and ship-ice collision, are considered to be the output of similar factors but different theories. For instance, if a ship navigates under the given ice conditions, the probability of stuck in ice will grow for the slowing ship speed. Apparently, the situation of ship-ice collision is contrary to the ice stuck situation, in which the high ship speed may result in damage on ship hull (McCallum et al., 1996).

Fig. 2. The structure of BN

Thus, the direct contribution factors of

occurrence probability and relevant consequences of two considered accident types are assumed to be ship speed, ice concentration and ice thickness. However, it is worth noting that the probability of ice stuck depends on all these three factors, which is similar to the situation discussed by Fu et al. (2016). For the node “ship-ice collision”, in the current paper, it does not refer to every collision or interaction happened between ship and ice, but the collision that may cause more or less damage to the ship hull. This node also has three parent nodes- “ship speed”, “ice concentration” and “ice thickness”. Moreover, the parameters of ice thickness and ice concentration are considered to directly influence the consequence of ice stuck. It means the heavier the ice condition is, the severer the consequence will be due to the high ice load, and when ships are stuck ice, the speed will fall to zero, which reveals that the consequence of ice stuck is not related to ship speed. While for the consequence of ship-ice collision, the contributing factors are the ship speed and ice thickness, but not including the ice concentration. That is in line with the real situation since if the collision happens, the level of hull damage depends on ship speed and ice thickness.

Risk of various accident types covers the occurrence probability and its consequence which is generally defined as the product of them:

$$Risk = \sum_i PC_i \quad (4)$$

Where P denotes the occurrence probability and C represents the severity of consequence. The subscript i can be associated with ice stuck and ship-ice. Therefore, the probability and consequence of each type of accident are as parent nodes of each risk value node, as shown in Fig.2. The composed risk can be calculated according to the ice stuck risk and ship-ice collision risk, thus set as the top node.

3.3 CPTs estimation

In a BN model construction process, the conditional probability tables (CPTs) are of great significance. In this study, the probability distribution of the nodes in the model has been estimated by digging the collected data and expert opinions are received for the lack of objective data. As mentioned in section 2, the CPTs of the nodes related to environmental parameters are based on navigation log data. And, in this section, the estimations of CPTs of four significant nodes “ice stuck”, “ice stuck consequence”, “ship-ice collision” and “ship-ice collision consequence” are conducted.

For ship-ice collision, Kotovirta et al. (2009) concluded that ship could avoid all the ice with speed at the open sea when ice concentration was lower than 70%. To investigate this situation, we consulted the captain of Yong Sheng who had 15 years’ sea experience at open sea and ice area. From his point of view, Yong Sheng won’t be much affected if the ship-ice collision happens under the ice condition that the ice concentration is lower than 50% and ice thickness is lower than 40 cm according to her maneuverability and structure reliability. The CPT in Table 2 has been constructed according to existing literature and

experts’ judgements (Zhang et al., 2013).

Table 2. CPT of node “ship-ice collision”

Ice concentration		lower than 50%			
Ice thickness		Lower than 40cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0	0	0	0
	No	1	1	1	1
Ice thickness		40-80cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.03	0.05	0.09	0.12
	No	0.97	0.95	0.91	0.88
Ice thickness		More than 80cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.13	0.18	0.22	0.35
	No	0.87	0.82	0.78	0.65
Ice concentration		50-70%			
Ice thickness		Lower than 40cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0	0.06	0.09	0.11
	No	1	0.94	0.91	0.89
Ice thickness		40-80cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.28	0.41	0.45	0.51
	No	0.72	0.58	0.54	0.48
Ice thickness		More than 80cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.36	0.47	0.55	0.61
	No	0.63	0.52	0.44	0.38
Ice concentration		more than 70%			
Ice thickness		Lower than 40cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.12	0.2	0.35	0.45
	No	0.88	0.8	0.65	0.55
Ice thickness		40-80cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.52	0.57	0.61	0.62
	No	0.47	0.42	0.38	0.37
Ice thickness		More than 80cm			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.58	0.67	0.77	0.82
	No	0.41	0.32	0.23	0.17
Ice concentration		lower than 50%			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0	0	0	0
	No	1	1	1	1
Ice concentration		50%-70%			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.37	0.42	0.46	0.52
	No	0.63	0.58	0.54	0.49
Ice concentration		More than 70%			
Ship speed		<5 kn	5-8 kn	8-11 kn	>11 kn
ship-ice collision	Yes	0.53	0.58	0.62	0.63
	No	0.47	0.42	0.38	0.37

Moreover, the consequence of accidents is discretized to three states, minor, major and

critical. Generally, for a specific ship, the hull damage in ship-ice collision is mainly related to ship speed and ice thickness. In order to develop the CPT of node “ship-ice collision consequence”, 80 sets of experiment data were collected which contain collision damage situation and corresponding ship speed and ice thickness (Li, 2014). Five experts including ice-going ship captains were interviewed and their judgements have also been incorporated in the CPT presented in Table 3.

Table 3. CPT of node “ship-ice collision consequence”

Ice thickness		lower 40 cm			
Ship speed		<5kn	5-8 kn	8-11 kn	>11kn
ship-ice collision consequence	minor	1	1	0.89	0.72
	major	0	0	0.11	0.18
	critical	0	0	0	0.1
Ice thickness		40-80 cm			
Ship speed		<5kn	5-8 kn	8-11 kn	>11kn
ship-ice collision consequence	minor	1	0.91	0.83	0.63
	major	0	0.09	0.14	0.22
	critical	0	0	0.03	0.15
Ice thickness		More than 80 cm			
Ship speed		<5kn	5-8 kn	8-11 kn	>11kn
ship-ice collision consequence	minor	0.95	0.88	0.78	0.53
	major	0.05	0.12	0.16	0.25
	critical	0	0	0.06	0.22

The estimation of CPT of node “ice stuck consequence” is maintained by consulting the ice-going ship engineers. They provide opinions about the level of ice load under different ice conditions when ship is stuck in ice. The similar research and results can be found in Fu. (2016). The CPT of node “ice stuck” which refers to ice stuck probability is constructing by digging the historical accident report and experts’ opinions. The probability of ice stuck has been studied by many researchers. Fu et al. (2016) adopted Bayesian Belief Networks (BBN) to analyze the probability of ice stuck to be 0.02. While Montewka et al. (2015) estimated ice stuck probability by developing the data-driven prediction model and the estimated probability was 0.03. In the current paper, after estimating the CPT of node “ice stuck” and other probabilities of its parent nodes, the occurrence probability of ice stuck is finally calculated to be 0.03 as shown in the Fig. 3, which can be acceptable by comparing to the probabilities estimated by other researchers.

After constructing the CPTs for the nodes in the presented BN model, the marginal probability for every node is calculated using Formula. (2). The complete Bayesian network model developed is shown in Fig. 3. Although, it is worthy noting that The motivation of current study is not to focus on quantitative accuracy or probability estimation, but to claim the proposed methodology and provide a risk perspective of bench mark for how to make decisions on ship speed adjustment to reduce the navigation risk.

Fig. 3. Marginal probabilities for developed BN model using GeNIe

4. Case study

Before conducting case study, it is worth noting that the influence of consequence of accident can be translated to a utility value and the following calculation can calculate it:

$$I_j = \sum_{i=1}^N V_{(i|j)} P_{(i|j)} \quad (5)$$

Where: I_j is the risk value (utility value) of accident given the evidence j , V_i is the influence value of the state i of the accident’s consequence, P_j is the probability of the state i of the accident given the evidence j , and N is the number of the states of the node. And, the severity of each state is shown in Table 4, which can be used to measure the risk value for the nodes “ice stuck risk” and “ship-ice collision risk”.

Table 4. The severity of consequence

Severity	Influence value
minor	10
major	100
critical	1000

In actual Arctic navigation, the information about ice concentration observed by crews is the main judgment about the ice condition of ice field, since the data about ice thickness is hard to obtain or the accuracy is very rough, while the information about ice concentration is more accessible and reliable. Thus, the case study aims to search the safe speed under different ice concentrations.

Through setting different evidence of ship speed under various ice concentration, the value of composed risk which is the joint risk value of both ice stuck and ship-ice collision will change and the ship speed corresponding to the minimum risk value can be found, which can be defined as

safe speed under this ice concentration.

The developed model can quantifiably indicate navigation risk with different ship speed in various scenarios. There are three scenarios discussed in the current study. The selection of scenarios is according to the states of node “ice concentration”. In the first scenario, the probability of the state “lower than 50%” of node “ice concentration” is set as 100%. Then we alter the states of node “ship speed” in sequence and updated the network after each alteration. The composed risk value of this scenario can be shown in the top node. Then, the state of ice concentration is altered to “50-70%” and “70-90%” sequential, and the same process can be conducted to obtain the composed risk value of each scenario.

5. Results

The ultimate simulation results are shown in Fig. 4. The developed Bayesian model indicates that, if the ice concentration of the ice-cover waters that a ship is sailing in is the lowest category (low than 50%, i.e., light ice conditions), the relatively high ship speed range, 11 kn to 14 kn, has the smallest risk value as 0.18. And, if the ice concentration is in the medium category, namely 50-70%, the safe speed is within 5 kn to 8 kn with the risk value of 7.8. When the ice condition is severe which refers to ice concentration is over than 70%, the safe speed range is below 5 kn with risk value of 22.26.

Fig. 4. Results of Safe speed simulation

6. Conclusion

The safe speed analysis in ice area is complicated because of many influencing factors that are difficult to quantify. The paper proposes a method to analyze the safe speed in ice-covered waters towards risk perspective. The major novelty for current paper is to consider two main accident scenarios, i.e., ice stuck and ship-ice collision, in a BN model. The probability and consequence of the occurrences of these two accident scenarios are estimated using different methods and then integrated to calculate the composed risk of accidents. Moreover, according to the results of the simulation, the safe speed range under various ice conditions can be identified. However, there exist certain limitations that require further research effort in the future. For instance, the

consequence of ice stuck is estimated by synthesizing information from literatures and experts opinions. It is better to analyze the consequence through ice load and structure reliability perspectives. Otherwise, due to the lack of data, the model developed can only provide a safe speed range. If more available data can be collected, the more precise safe speed can be gained.

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