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Risk Assessment of Inward and Outward Ships Based on Bayesian Network

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Abstract: As the main means of exporting, shipping industry undertakes the responsibility of developing the national economy. In what concerns the shipping industry, the safety of human beings and the cargoes on board has been investigated for many years. Whereas it is still challenging due to the incomplete data resource and the uncertainty in the model. In this paper, for the sake of assessing the risk of inward and outward ships, Bayesian Network (BNN), which integrates the data resource of accidents with the expert knowledge to quantify the uncertainties, is presented. Firstly, variables are conducted in the network by comprehensively analyzing the factors which influence the safety of the ships in the vicinity of the area. Secondly, a topology and the direction of the arcs are determined by calculating the relevancy among variables nodes. And a conditional probability table is obtained by combining historical data of Qingdao port and the expert knowledge. Finally, to verify the validity of the proposed model, the sensitivity of the relevant node is evaluated. Simultaneously, the risk evaluation index and navigation safety recommendations are demonstrated.
Keywords: Bayesian Network; Risk Assessment; Navigation Safety; Qingdao Port.

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1. INTRODUCTION

Carriage of goods by sea play a pivotal role in the development of marine economy (Ming, 2010). In what concerns the carriage, the safety of the crew and cargoes on board has been investigated in various methods in recent years. Fortunately, with the development of the automation, the probability of accidents decreases in a certain way. However, the risk remains in the transportation especially in the complicated area like the entrance or exit of the port, of which the high density of traffic flow, the complexity of encounter situation, and the depth of the lane etc. proliferate the navigation risk (Quanjin, 2011). Hence, it is essential to assess the risk of inward and outward ships considering relevant factors which are the efficient way to ensure the safety of the crew and the cargoes on board. The definition of risk could be represented by event A, result C, and probability P, that is risk ~ (A, P, C) (Goerlandt and Kujala, 2014). And the risk assessment is basically an evaluation process based on a scientific structure with uncertainty (Coleman and Marks, 1999). The role of the risk assessment can be concluded to be the solution for the problems such as “what problems will arise?”, “what are the potential consequences?” and “what is the probability of this happening?" (Ayyub *et al.*, 2010). In the past two decades, risk assessment has been a hot topic in the shipping industries. As the consequence, the International Maritime Organization (IMO) proposed a systematic Formal Safety

Assessment (FSA) for risk assessment to help conduct safe decision management (Kontovas and Psaraftis, 2009). In particular, the standard FSA consists of five steps: 1. Hazard identification; 2. Risk assessment; 3. Risk control options; 4. Cost-benefit assessment; 5. Decision making.

Besides FSA, a variety of methods have been applied to risk assessment over the past few years, including Hazard and Operability Studies (HAZOP) (Palmer and Chung, 2009), Failure Mode and Effects Analysis (FMEA) (Emovon, 2016), Fault Tree Analysis (FTA) (Senol and Sahin, 2016), Event Tree Analysis (ETA) (Fu *et al.*, 2017) and Bayesian Network (BNN) (Afenyo *et al.*, 2017). Owing to the advantages of BNN compared with other methods like succinct and clear explanation of causality, ability to make forward and reverse inference, ability to combine historical data with expert experience, ability to deal with uncertainty, and ability to update corresponding conclusions based on new information or observations, the number of the papers using BNN augments from 0 to 16 between 2004 and 2013 (Hänninen, 2014). And the research on risk assessment using BNN becomes a hotspot in recent years (Ren *et al.*, 2008; Trucco *et al.*, 2008; Li *et al.*, 2011; Floris and Jakub, 2014; Goerlandt and Montewka, 2015; John *et al.*, 2016; Zhang *et al.*, 2016; Baksh *et al.*, 2018).

BNN is a specific type of quantitative causal model, which consists of a directed acyclic graph and a set of probability tables, constructed based on the Bayesian principle to model the uncertainty of a system (Nadkarni and Shenoy, 2001). The capability of statistical analysis in the case of limited data (Modarres, Kaminskiy and Krivtsov, 2009), the ability to describe the conditional probability distribution or Conditional Probability Tables (CPT) of various variables in the system with different data sources or information, and the ability to inherent causality and complex relationships in the system (Groth and Mosleh, 2012) drive BNN to be an efficient way to the risk assessment.

In order to cope with the potential risks brought by uncertain factors in the dynamic environment to offshore operations, J. Ren et al. proposed a fuzzy Bayesian network for risk assessment combined with expert knowledge (Ren et *al.*, 2009). P. Trucco et al. conducted a BNN to evaluate the risk of maritime industry on the impact of human factors and organizational factors. The method is supposed to support the identification and assessment of risk control options in different ways, especially at the organizational level (Trucco *et al.*, 2008). To study the risk of oil spilling in collision accidents (including product tankers), G. Floris et al. constructed a BNN to conduct an evolutionary reasoning on collision accidents under the condition of incomplete data and uncertainty (Floris and Jakub, 2014). As the aspect for the risk assessment of ship collisions, some similar research were studied on the literature (Wiel and Dorp, 2011; Dong and Dan, 2015; Goerlandt and Montewka, 2015; Chai, Weng and Xiong, 2017; Christian and Kang, 2017), in which the main difference among them is that the variable nodes considered in the model are inconsistent. In addition to the collision risk assessment of ships, the risk assessment of stranding and oil spilling using BNN has been studied. A. Mazaheri et al. involved in the risk assessment of ships stranding by constructing BNN model, then analyzed the uncertainty and sensitivity of the model to determine which waters that need more research (Mazaheri, Montewka and Kujala, 2016). T. Lecklin et al. have assessed the risk of oil spilling accidents to aquatic life on the Gulf of Finland by constructing a BNN model (Lecklin, Ryömä and Kuikka, 2011).

Though considerable effects especially certain types of accidents such as collision or stranding have been devoted to the investigation of risk assessment using BNN, few studies focused on the general risk assessment of inbound and outbound vessels. In this case, the paper investigates the general risk assessment of inward and outward ships using BNN. After the comprehensive analysis of the safety factors which would be the evidence to be the variable nodes in BNN, the risk is supposed to be divided into several levels: a) Major accident; b) Serious accident; c) Accident with wider consequences; d) Accident with local consequences; e) Incident. By means of calculating the relevancy among variable nodes, the topology of BNN is then constructed and the CPT is obtained by incorporating the historical data of Qingdao Port with expert knowledge. Finally, to verify the validity of the proposed model, the sensitivity of the relevant nodes is evaluated. Simultaneously, the risk evaluation index and navigation safety recommendations are demonstrated.

The remainder of the paper is organized as follows. In Section 2, we introduce the fundamental of BNN. In Section 3, we present the system model of risk assessment integrated the historical data with expert knowledge. In Section 4, we evaluate the proposed model and propose the navigation recommendations in the entrance and exit of Qingdao Port. In the last section, Section 5, we conclude this paper.

2. FUNDAMENTAL OF BNN

2.1 Structure of BNN

BNN is a probability graph model that represents the conditional and independent relationship among random variables through a Directed Acyclic Graph (DAG) (Achumba *et al.*, 2013). A DAG consists of nodes and directed arcs of which each node represents a variable in the system and each variable contains a finite number of states. For a discrete BNN, the state of each node can be binary (yes/no, true/false, success/failure), or multiple states (Yang, 2014). In a BNN, the directed arc is generally used to indicate the causality between the nodes, and the arrow indicates the direction of the causality. The determination of each variable in BNN is based on the research objectives combined with expert knowledge. In what concerns BNN, the causality, which could be determined by relevancy analysis when the data are available, is one of the main forms of the relationship between two variables (Ruggeri, Kenett and Faltin, 2007; Yunlong *et al.*, 2013). Generally, the relevancy between two variables can be fixed using the Pearson correlation coefficient that is known as the Pearson product-moment correlation coefficient (PMCC). The PMCC could be expressed as,

$$C_{PMCC} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \tag{1}$$

where X and Y represent the data sets which contain n samples respectively. X_i and Y_i indicate the i^{th} sample in respective data sets. $\bar{X}$ and $\bar{Y}$ denote the average of the data respectively. C_{PMCC} is the correlation coefficient with the range of $[-1,1]$. When $C_{PMCC} = 0$, $C_{PMCC} = -1$, and $C_{PMCC} = 1$, it indicates the two variables are irrelevant, negatively corrected, and positively corrected respectively. Nevertheless, the correction analysis can only help to explore the relevancy between two variables (Kołowrocki and Kwiatuszewska-Sarnecka, 2008). As for the direction of arcs in BNN needs to be further studied by factor analysis.

2.2 Quantification of BNN

Each node in BNN, of which the directed arcs represent the master-slave relation among nodes, is normally assigned a marginal probability or a CPT based on the data and expert knowledge (Khakzad, Khan and Amyotte, 2013).

Let $V = \{X_1, X_2, \cdots, X_n\}$ be the set of all variables. Thus, the conditional probability $P(V)$ can be expressed as,

$$P(V) = \prod_{i=1}^{n} P(X_i|Parents(X_i)) \tag{2}$$

where $Parents(X_i)$ represents the parent node for X_i. The joint probability of variable nodes in BNN is acquired by a set of CPTs. A CPT indicates the conditional probability for all possible states of the parent variable nodes.

The conditional posterior probability distribution and the joint probability distribution can be demonstrated as Eq. (3) and Eq. (4) respectively.

$$P(X_j|X_i) = \frac{P(X_j)P(X_i|X_j)}{P(X_i)} \tag{3}$$

$$P(X_i, X_j) = P(X_i)P(X_j|X_i) \tag{4}$$

CPT could basically be populated by expert knowledge incorporated with historical observation data. If each node has m states and n parent nodes with l states, the CPT will have $m * n^l$ columns where the sum of each column in the CPT is equal to1.

2.3 Inference of BNN

After the corresponding CPT for each node is acquired, the process of quantification of BNN is to some extent completed, which means the prior information of BNN is determined. The information of variable nodes will be updated once new data sets are obtained. The update process is carried out repeatedly whenever the data are available. The information of the data broadcasts automatically through the BNN, and the state of variable nodes renew. In particular, the updated probability of each node is the consequence of the prior information and the data received.

3. MODEL OF THE RISK OF INWARD AND OUTWARD SHIPS

3.1 Risk influencing factors

The safety of inward and outward ships is influenced by the environment, human factors, the status of ships nearby, navigation aids and its own status (Chai, Weng and Xiong, 2017). Though many studies considered the human factors as the main cause of the accidents, this paper investigates the risk assessment of inward and outward ships by the ship itself and the environment in terms of objective factors. According to the relevant studies (Ren *et al.*, 2008; Trucco *et al.*, 2008; Eleye-Datubo *et al.*, 2010; Yunlong *et al.*, 2013; Yang, 2014; Mazaheri, Montewka and Kujala, 2016; Chai, Weng and Xiong, 2017; Baksh *et al.*, 2018) and the expert knowledge integrated with the historical data by Qingdao port (Guixue *et al.*, 2011), the influencing factors are shown in Figure 1.

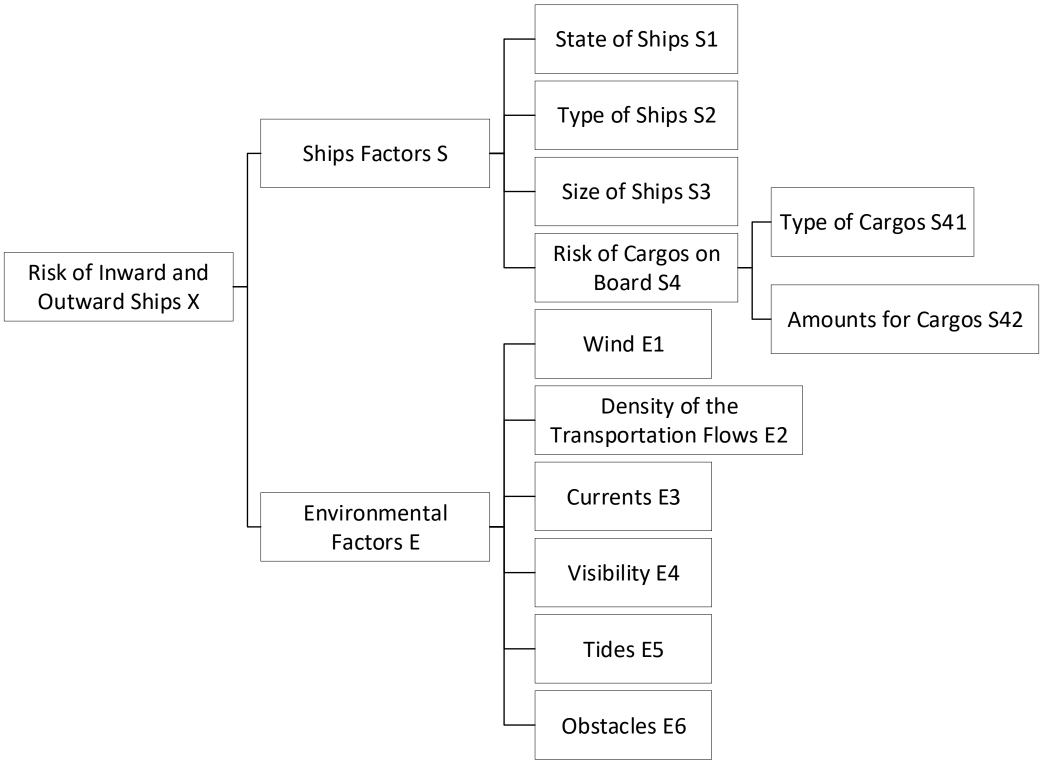

Figure 1. Risk influencing factors for inward and outward ships

As shown in Figure 1, X represents the risk of inward and outward ships which is divided into two layers: 1) the ship factor S; 2) the environmental factor E.

In what concerns the first layer, ship factors, and the status of the ship including navigation, mooring, berthing and others is a paramount factor on the research of risk assessment(Ren *et al.*, 2008; Eleye-Datubo *et al.*, 2010). Similarly, the difference in ship type and size makes the different maneuvering in the arrival or departure. Therefore, the ship type and size should be considered in the risk influencing factors (Trucco *et al.*, 2008). Moreover, the genre and the amount of the cargoes could exert an extra moment in the stability of ships which would to some extent augment the risk of accidents. In this case, the risk of cargoes on board contributes to the ship factors (Ren *et al.*, 2008; Trucco *et al.*, 2008; Baksh *et al.*, 2018). With regard to the second layer, environment factors, and most of the factors including wind, current, traffic density, visibility, tides and obstacles in this layer are basically uncontrollable and dynamic but predictable (Yunlong *et al.*, 2013; Yang, 2014; Mazaheri, Montewka and Kujala, 2016; Chai, Weng and Xiong, 2017).

3.2 BNN model for inward and outward ships

3.2.1 Data resources

Three means are exploited commonly to conduct the structure of BNN model using data (Guoping, 2005): 1) Expert knowledge; 2) The historical database; 3) Expert knowledge integrated with the historical database. In this paper, the last method is utilized to conduct the BNN.

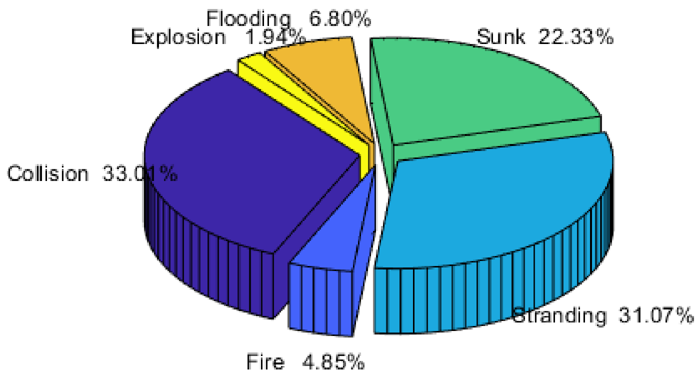

Figure 2. Accidents statistics from 1999 to 2010

The expert knowledge database that we utilize in this paper is based on (Yunlong, 2014). The database was constructed by means of the questionnaire and extensive discussion with experts. In order to overwhelm the subjectivity by the experts, we use the historical data to correct them. According to the statistics in (Songhu, 2011; Guixue, 2012; Wenjin, 2015; Zhu *et al.*, 2015; Minghui *et al.*, 2017), 103 accidents happened including 34 collisions, 32 stranding, 23 sunk, 7 flooding, 5 fire and 2 explosions in approaching Qingdao Port from 1999 to 2010. The proportion of each accident and the specific number of each accident are shown in Figure 2 and Figure 3 respectively.

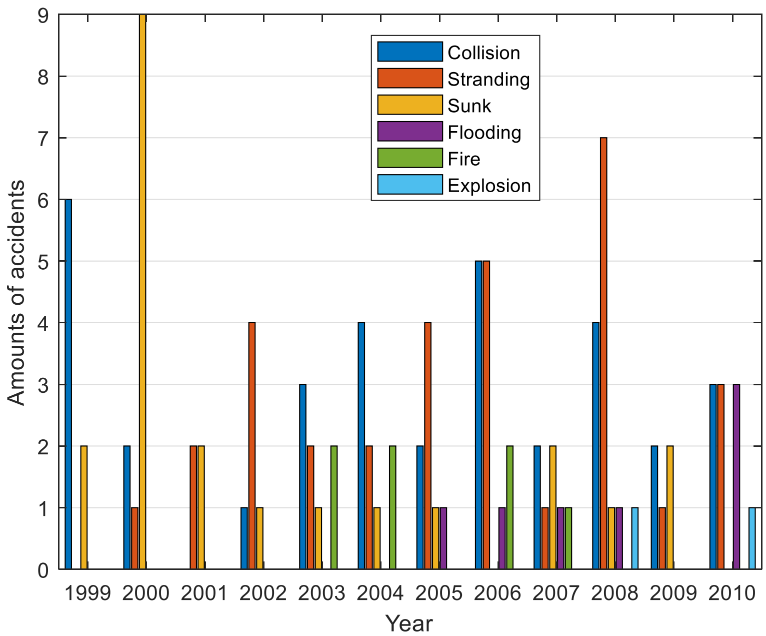

Figure 3. The specific number of each accident from 1999 to 2010

3.2.2 Structure of BNN

Generally, the nodes in BNN can be determined according to the risk influencing factors. Nevertheless, not all factors can be considered as BNN nodes due to the lack of data. Therefore, the final network nodes in the model are determined based on expert knowledge and the data in (Songhu, 2011; Guixue, 2012; Wenjin, 2015; Zhu *et al.*, 2015; Minghui *et al.*, 2017). Each state of the nodes is presented based on the classification criteria adopted by the Maritime Safety Committee (MSC)

(*MaritimeSafetyCommittee(MSC)(1995).RESOLUTIONA.823(19).*, no date) and the corresponding literature (Montewka *et al.*, 2013, 2015). The state of each variable node is shown in Table 1.

Table 1 Variable nodes state in BNN

Risk of inward and outward ships X	High/Moderate/Low	Ship Factors S	High/Moderate/Low
Ships statusS1	Navigation/ Arrival & departure the port/ Anchorage/Others	Ships type S2	Danger/Container/ Bulk/Others
Ships size S3	Small/General/Huge	Risk of cargos S4	High/Moderate/Low
Cargos type S41	Danger/Heavy/General	Cargos amount S42	Full/Half/Empty
Environment factors E	High/Moderate/Low	Wind E1	Big/General/Small
Traffic density E2	Small/Big	Currents E3	Small/Big/General
Visibility E4	Good/Poor/Extreme		

The relevancy between nodes, that is, the direction of the arc in BNN is usually determined by the value of the PMCC. If the absolute value of the correlation is greater than 0.3 between two random variable nodes, it indicates that they are related. Moreover, if the value is positive for the reference node to another, it means the direction of the arc is from the reference node to another one. if the value is negative for a node to another, it means the direction of the arc is from the other nodes to the reference node. According to the Equation (1) incorporated with the data, the relevancy of each node is demonstrated in Figure 4.

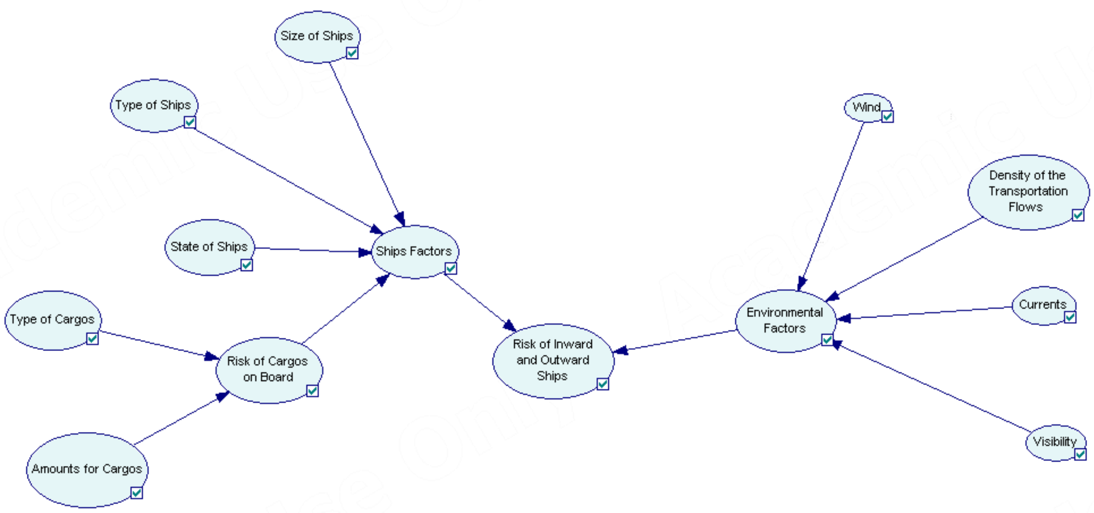

Figure 4. Risk model of inward and outward ships in BNN

3.2.3 CPT of BNN

To further improve the BNN model established in Section 3.2.2, the probability of each node and CPTs are constructed combining the data sources mentioned in Section 3.2.1. Due to the space limitation, only the CPT of the risk of cargoes is shown in Table 4.

Table 2. Variable nodes probability in ships factors

	States			
Ships size	Small	General		Huge
	0.47	0.45		0.08
ships Type	Danger	Container	Bulk	Others
	0.16	0.44	0.26	0.14
Ships status	Navigation	Arri.& Depart.	Anchorage	Others
	0.56	0.18	0.09	0.17
CARGOS TYPE	Danger	Heavy		General
	0.14	0.15		0.71
CARGOS AMOUNT	Full	Half		Empty
	0.21	0.38		0.41

Table 3. Variable nodes probability in environment factors

	states		
Wind	Small	General	Huge
	0.3	0.5	0.2
traffic density	Small		Big
	0.4		0.6
currents	Small	General	Big
	0.2	0.5	0.3
visibility	Good	Poor	Extreme
	0.6	0.25	0.15

Table 4. The conditional probability of the risk of cargos

	Cargos type	Danger			Heavy			General		
	Cargos amount	Full	Half	Empty	Full	Half	Empty	Full	Half	Empty
S4	High	0.8245	0.7623	0.3219	0.7623	0.7073	0.3245	0.4573	0.4032	0.3333
	Moderate	0.1304	0.2318	0.4528	0.2014	0.253	0.4032	0.3024	0.3302	0.3333
	Low	0.0451	0.0059	0.2253	0.0363	0.0397	0.2723	0.2403	0.2666	0.3334

As for the CPT of ships factors S according to Table 2, it contains 3 rows and 144 columns of data. With regard to the CPT of environmental factors E, it contains 3 rows and 54 columns of data. Due to the lack of the accidents historical data, the calculation of CPTs is based on the database in the literature (Yunlong, 2014) integrated with the incompleteness data.

4. SIMULATION

In order to verify the validity of the proposed model, GeNIe and Matlab 2016b are used to perform experiments on a 64-bit Window 10 system with a CPU at 3.6 GHz and a memory of 8 G.

According to Section 3 wherein the acquisition of model nodes, directions and CPTs are conducted, a BNN model of navigation risk for inward and outward ships is established, as shown in Figure 5. To further explore the sensitivity of the proposed model, we consider a node as the output to observe the change of the rest of the nodes (Hosseini and Barker, 2016). For the calculation of sensitivity, the first thing that we should do is to conduct the response function $F(x) = g(X), X = x_1, x_2, \cdots, x_n$, and the partial derivative of the response function for the variable x_i is the sensitivity of the variable.

$$S_i = \frac{\partial F}{\partial x_i} \tag{5}$$

where the absolute value of S_i reflects the sensitivity of the corresponding function to the variable.

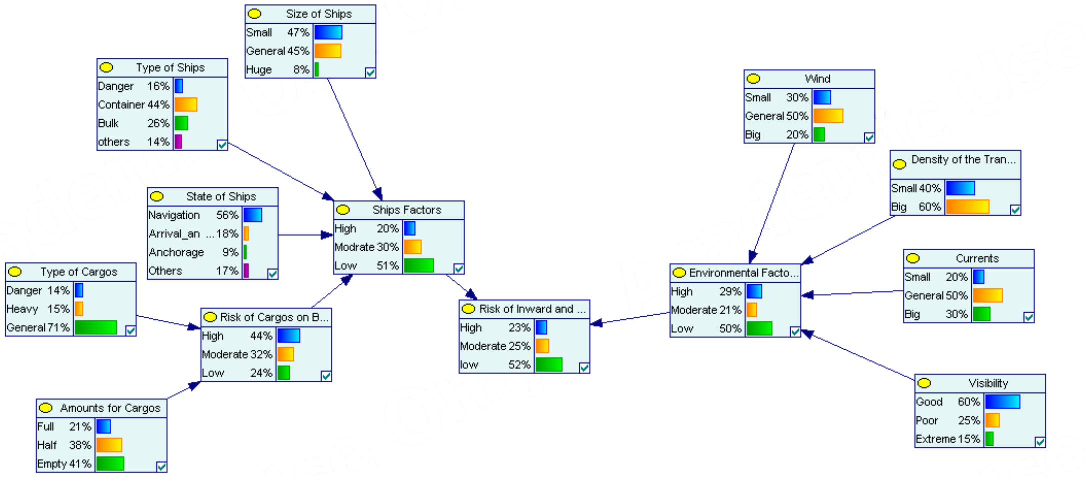

Figure 5. Risk probability of inward and outward ships in BNN

This paper mainly focuses on the risk assessment of inward and outward ships, and providing advice for port authority and vessels navigating in the vicinity of the port. Therefore, we consider the navigation risk X as the output, and the state we set is high. According to Equation (5) and the corresponding data source, the sensitivity is obtained and shown in Table 5.

Table 5. Risk sensitivity of inward and outward ships

Number	Variables	Sensitivity
1	Visibility	0.9058
2	Traffic density	0.8147
3	Ships type	0.7824
4	Ships size	0.6954
5	Risk of cargos	0.6118
6	Ships status	0.5622
7	Cargos type	0.5569
8	Wind	0.3712
9	Current	0.2557
10	Cargos amounts	0.1862

It can be seen from Table 5 that the value of the sensitivity of visibility is the largest than the others, which indicates that the probability of accidents happening will increase dramatically if the visibility is poor in Qingdao port. The value of the sensitivity of cargos amounts is the smallest compared with other factors, which means the cargos amounts contribute a little to the accidents happening.

It should be noticed that the results obtained by the proposed model in this paper are the probability of various types of accidents. To further quantify the risk of inward and outward ships, it should combine with the consequences of the accidents. By means of the current statistical law of marine accidents (Shenping, Quangen and Haibo, 2005), the consequences of accidents are assigned according to the level. The assignment of the consequences of the accidents is shown in Table 6.

Table 6. Assignment for the consequence of the accidents

Number	1	2	3	4	5
Level	Major accident	Serious accident	Accident with wider consequences	Accident with local consequences	Incident
Coefficient	50	10	6	1	0.1

In accordance with the definition of the risk of inward and outward ships, the risk value can be acquired by integrated the accident probability with the consequences of the accidents.

$$R = \sum_{i=1}^{n} P_i \times C_i \tag{6}$$

where P_i is the probability of the i^{th} event. C_i is the consequence of the i^{th} event.

The relevant risk values could be calculated according to Equation (6), and the results are: the risk value of ship factors $R_s = 5.37$, the risk value of environment factors $R_e = 5.16$, and the risk value considering two factors $R_{se} = 6.33$. It can be seen from the risk values that the ship factors and the environmental factors are positively coupled, and the overall risk value after coupling is greater than the single risk value before coupling.

The advice for inward and outward ships can be concluded after comprehensive sensitivity analysis and risk calculation analysis:

Ship factors and environmental factors have a great negative impact on inward and outward ships especially the poor visibility and high traffic density. When suffering the poor visibility and high traffic density situation, the officer on duty must drive carefully and cautiously. Some relevant safety measures should be taken including slowing down the speed, proactively contacting the vessels nearby and the traffic management department of Qingdao port, and strengthening the means of observation.

Among the ship factors, the ship type has a greater impact on the risk of inward and outward ships than other factors. Different measures should be taken according to the different ships in the vicinity of Qingdao port to minimize the risk. It could be noted that the probability of accidents during navigation is the highest, which indicates that special monitoring should be taken when the ships are in navigation.

Although the wind has a lower sensitivity to the risk of inward and outward ships compared to other factors, the impact of the wind is indeed not negligible. Especially for the windy area of Qingdao port, the strong wind will seriously affect the anchorage and navigation. It is recommended that the officer on duty should navigate against the wind or anchoring if necessary when suffering the strong wind.

5. CONCLUSION

This paper utilizes the BNN to conduct a risk assessment for inward and outward ships. Firstly, after comprehensively analyzing the risk influencing factors for inward and outward ships, the risk is divided into several levels and the variable nodes for BNN are determined. Secondly, by means of calculating the correlation between the variable nodes, the direction of the arc for each node is obtained, and the topology of BNN is conducted. Thirdly, the CPTs are acquired using expert knowledge incorporated with the historical data of Qingdao port. Finally, to verify the effectiveness of the proposed model, sensitivity values and risk values are calculated respectively. Simultaneously, the navigation recommendations are illustrated after comprehensive sensitivity analysis and risk calculation analysis. However, the proposed model is limited which only considers the static risk assessment. Future work will focus on the dynamic risk assessment in BNN.

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