Risk Bayesian Assessment Approach to HOF-based Ship Operation in Harbour

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Abstract –**Marine accidents were mostly caused by the human errors, and it is important to emphasize the research about the human elements for the safety of ships. Risks based on human organization factor (HOF) associated with the vessel operation system at sea are analyzed according to the elements in this system and a new method of proposed risk assessment(PRA) is developed to ensure safe ship operation including the framework, content and procedure. Based on Bayesian method, Bayesian estimation, learning, reasoning and decision-making are established for the quantitative risk assessment (QRA) of the vessel operation system at sea. After the analysis on occurrence probability of accidents related to ship pilots in harbour, a thorough procedure about proposed risk assessment on the basis of Bayesian method is developed to obtain the QRA of their relative distributions. The distributions of ship operation are described and results are presented on QRA in relation to various features. This method, verified in the cases of QRA, turns out to be feasible in the application of risk assessment.**

Key words: **Ship, hazard identification, risk assessment, risk control, safety, human organization factor, ship pilotage, safety factor**

I. INTRODUCTION

Despite the remarkable effort performed at different levels to achieve a safe Maritime Transport System (MTS), the occurrence of accidents and incidents at sea is still increasing[1]. China Maritime Administration reveals that maritime accidents at sea are responsible yearly for 500 deaths and 164 million RMB of goods loss and damages. Collision, aground, and contact is the most frequent occurrences and they have the highest rate of casualties. Globally, the MTS is responsible for 0.33 deaths per 100 million person-km, 4 times riskier than the air transport system, that accounts for 0.08 deaths per 100 million person-km（Statistics published by the European Transport Safety Council）.

Risk has a random uncertainty. In the case of model uncertainty, when there exist several possible models to describe a phenomenon, a Bayesian approach can be used to include all the candidate models by assigning model weight (the probability of each model being correct) and integrating the effects of all the models. When there are observations/data available, the model may be updated and shifted to the more appropriate model. This approach has been applied to the uncertainty of probability distribution type and linear regression model uncertainty problems in statistics, and was recently used to account for human model uncertainty[2].

As it is known to all, the marine accidents were mostly caused by the human errors, and it is important to emphasize the research about the human elements for the safety of ships. There are many conventional ways used to assess the safety of the ships, such as the Event Tree Analysis (ETA), Probabilistic Risk Assessment (PRA) and so on, but apart from these conventional ways for the investigation, statistics and analysis of the human elements in the marine accidents, the Formal Safety Assessment (FSA) [3], as a modern advanced and efficient way, can be used to support and enhance such research works. It has been gradually and broadly used in the shipping industry nowadays around the world. Furthermore, Human Organization Factor(HOF)[4] is nowadays held on to solve the question in such relative field as safety research areas, which can be viewed as an elements of human-machine system, specially for transportation at sea.

FSA was initially studied at the 62nd IMO Maritime Safety Committee (MSC) meeting in 1993. At the 65th meeting of the MSC in 1995, strong support was received from the member countries and a decision was taken to make FSA a high priority item on the agenda of the MSC. An international FSA Working Group was established at MSC 66 in 1996 and MSC 66 in 1997 draft international guidelines of FSA were generated, including all key elements of the FSA framework developed by the UK[4]. Since then, some of the member countries have carried out the research projects for the application of FSA to the safety of ship, including the high speed passenger catamaran ferries, bulk carriers and other kind of vessels.

This paper, on the basis of analysis on the framework and procedure of proposed risk assessment in a ship operation system at sea, involves a Bayesian method, in which the risk assessment model of the ship operation system, specially for HOFs-based system is established. Furthermore, using Bayesian statistics, reasoning learning and predication of risk applied a case of risk assessment to ship pilotage in Shanghai harbour.

II. PROPOSED RISK ASSESSMENT METHODOLODGE

Formal safety assessment is an approach to maritime safety which involves using the techniques of risk and

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cost-benefit assessment to assist in the decision making process. But some steps are difficult to apply in the concerned and actual problem which involved so many human errors , such as the cost-benefit analysis in ship-pilotage safety in harbour and navigation safety at sea. Hence, a proposed risk assessment (PRA) methodology can be held out on the basis of FSA. The brief introduction to the PRA is as follows.

A. The Aim and Characters of PRA

Proposed risk assessment is also the process of identifying hazards, evaluating risks annd deciding on a course of action to manage the risks. It is a structured and systematic methodology, aiming at enhancing maritime safety, including protections of life, health, the marine environment and property. Through the its five formal assessing steps (including identification of hazards, assessment of risks associated with those hazards, development and evaluation of alternative ways of managing the risks, predication or alert of these risk in the near future and options or recommendations for decision making, see fig 1), it can be used as a tool to help in making the new options or measures to prevent or reduce the concerned accidents, or having a comparison between existing and possibly improving measures, with a view to achieving a balance between the various technical and operational issues including the human organization factors. Therefore, it is expected that the PRA Study will be of assistance in framing well-founded recommendation on the risk prevention and reduction.

B. The Conduct and Practice of PRA

The PRA framework consists of the following five steps, including the identification of hazards, the assessment of risks associated with those hazards, ways of managing the risks identified, cost benefit assessment of the options, decisions on which options to select (Figure 1).

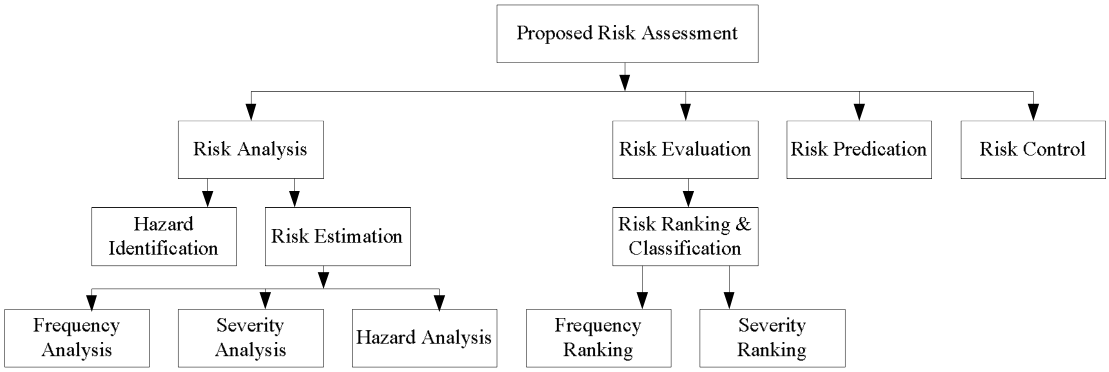

Fig 1 Contents and procedure of proposed risk assessment

a. Analysis of Risks

This step aims at identifying and generating a selected list of hazards specific to the problems under review. In the process of PRA, a hazard is defined as "a physical situation with potential for human injury, damage to property, damage to the environment or some combination". Hazard identification is concerned with using "brainstorming" technique involving trained and experienced personnel to determine the hazards. An accident is defined as "a status of the vessel, at the stage where it becomes a reportable incident which has the potential to progress to loss of life, major environmental damage and/or loss of the vessel".

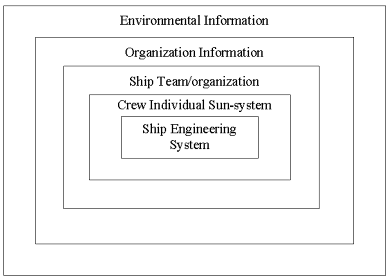

Fig 2 HOF framework in an operation system

HOF issues should be systematically dealt with in the FSA framework. Significant risks can be chosen in this step by screening all the identified risks, specially in maritime field[5](see fig 2). Various scientific safety assessment approaches such as Preliminary Hazard Analysis (PHA), and Failure Mode, Effects and Criticality Analysis (FMECA) can be applied in this step.

b. Evaluation of Risks

This step aims at assessing risks and factors influencing the level of safety. Risk assessment involves studying how hazardous events or states develop and interact to cause an accident. Shipping consists of a sequence of distinct phases between which the status of ship functions changes. A ship operation system[6] consists of a set of systems such as individual of crew(captain and officer), pilotage system, ship machine system, environmental system. A serious failure of a system may cause disastrous consequences. Risk assessment may be carried out with respect to each phase of shipping and each marine system. The likelihood of occurrence of each failure event and its possible consequences can be assessed using various safety assessment techniques. An influence diagram may be used to deal with the escalation of an accident and mitigation aspects such as the evaluation of people, containment of oil pollutants, etc. Generic data or expert judgments may be used in risk assessment.

When Quantitative Risk Assessment (QRA) [6] is performed, it is required to use numerical risk criteria. The shipping industry has functioned reasonably well for a long time without consciously making use of risk criteria. As time goes on, it is believed that more QRA will be conducted in the marine safety assessment. Therefore, numerical risk criteria in the shipping industry need to be dealt with in more details.

c. Predication of Risks

This step aims at finding out the risks' characteristics in the near future. This is the task of computing the risk distribution over the near future state, given all evidence to date. After the assessment of risks, the rank and classification can be shown as the designated the accidents or hazards. Owing to these history data, sometimes they can not be viewed as the efficient data or evidence to describe the trend of the near future. So its reliability should be checked after the time span. Normally, the Bayesian theory always can be involved to analyze the reliability of the founded high risk. such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Failure Mode and Effect Analysis (FMEA) can be used to assist in this step.

d. Risk Control Options

This step aims at proposing effective and practical risk control options. High risk areas can be identified from the information produced in the risk assessment and then the identification of risk control measures can be initiated. In general, risk control measures have a range of following attributes:

a) Those relating to the fundamental type of risk reduction (i.e. preventative or mitigating).

b) Those relating to the type of action required and therefore to the costs of the action (i.e. engineering or procedural).

c) Those relating to the confidence that can be placed in the measure (i.e. active or passive, single or redundant).

Risk control measures can reduce frequency of failures and/or mitigate their possible efforts and consequences. Structural review techniques may be used to identify all possible risk control measures for decision-making of risks.

e. Decision Making of Risks

This step aims at making decisions and giving recommendations for safety improvement. The information generated can be used to assist in the choice of cost-effective and equitable changes and to select the best risk control option.

In the process of making, decision criteria may be used to determine if risks are acceptable, unacceptable or need to reduce to ALARP. All measures can be taken into account such as 3E(Education, Enforcement and Engineering).

III. BAYESIAN THEORY

Bayesian theory has made great achievements covering most research areas in artificial intelligence (AI), which includes deduction of causality, description of uncertainty, identification of modes and clustering analysis. The achievements have been introduced to the study of risk analysis recently [7,8].

A. Bayes' point estimation of likelihood

Assume that sample set $A_1, A_2, \cdots A_n$ constitutes a complete and independent universe Θ. $A_i (i \in [1,n])$ is the occurred events in E and B refers to one existing event $p(B) \neq 0$ .It can be concluded that that the formula of the Bayes' rule can be expressed in accordance with the following Eq.(3):

$$P(A_i \mid B) = \frac{P(B \mid A_i)P(A_i)}{\sum_{j=1}^{n} P(B \mid A_j)P(A_j)}, i = 1, 2, \cdots n \qquad (1)$$

At the occurrence of A_j , the discrete random parameter θ is defined as $\theta = \theta_j = A_j (j = 1, 2, \cdots n)$, when the probability should conform to the following equation:

$$\pi(\theta_j) = P(\theta = \theta_j) = P(A_j), j = 1, 2, \cdots n \qquad (2)$$

Therefore, $\{\pi(\theta_j), j = 1, 2, \cdots n\}$ constitutes the prior probability distribution of random variables. This probability can be achieved on the basis of historical statistics or subjective judgments on the probabilities of incidents. Prior probability can normally be identified through three approaches mentioned above.

Suppose X, a discrete random variable related to B, accords with the following Eq.(5):

$$X = \begin{cases} x_1, \ when\ B = yes \\ x_2, when\ B = no \end{cases} \qquad (3)$$

From the equation (1), we can deduct the posterior probability (or conditional probability) under the condition of B occurred:

$$\pi(\theta_i \mid X = x_1) = \frac{P(x_1 \mid \theta_i)\pi(\theta_i)}{\sum_{j=1}^{n} P(x_1 \mid \theta_j)\pi(\theta_j)}, i = 1, 2, \cdots n \qquad (4)$$

As a result, this kind of probability distribution $\{\pi(\theta_i \mid x_1), i = 1, 2, \cdots n\}$ can be viewed as the distribution of $\{\pi(\theta_j), j = 1, 2, \cdots n\}$ through the sample observation x .

B. Bayesian network structure learning

A Bayesian network (BN) is used to model a domain containing uncertainty in some manner. In the past, the term causal probabilistic networks have been used. A BN is a directed acyclic graph (DAG) where each node represents a random variable. Each node contains the states of the random variable it represents and a conditional probability table (CPT) or in more general terms a conditional probability function (CPF). The CPT of a node contains probabilities of the node being in a specific state given the states of its parents. The following example demonstrates what all this means.

Assuming variables set X and a discrete variable θ representing uncertainty of network structure, its hypnoses of possible network is S^h, and its prior probability conforms to $P(S^h)$. Under the condition of random samples D, its posterior probability is $P(S^h \mid D)$.

$$P(S^h \mid D) = \frac{P(S^h, D)}{P(D)} = \frac{P(S^h)P(D \mid S^h)}{P(D)} \quad (5)$$

where $P(D)$ is a normalized constant.

One highly practical Bayesian learning method is the naive Bayes learner, often called the naive Bayes classifier. Probably the most common network model used in Bayesian learning is naive Bayes model. In this model the class variable X is the root and the attribute variables A are the leaves. With observed attribute values $a_1 \quad a_2 \quad \cdots \quad a_m$, the likelihood of each class is given by Eq.(6)

$$P(X \mid a_1 \quad a_2 \quad \cdots \quad a_m) = \alpha P(X) \prod_{j}^{m} P(a_j \mid X) \quad (6)$$

C. Bayesian parameter learning

The structure of the Bayes net is given and the parameter is trying to be learnt. Up to this point we have estimated probabilities by fraction of times the event is observed to occur over the total number of opportunities. To avoid difficulty this paper adopts a Bayesian approach to estimating the probability using the *m*-estimation defined as follows Eq.(7).

$$P(a_j \mid x_i) = \frac{n_c + mp}{n + m} \quad (7)$$

Here, n is defined as total number of training examples for which x_i occurred and n_c is the number of these for which a_j occurred. p is our prior estimate of the probability we wish to determine, and m is a sample size constant.

D. Bayesian Reasoning and Probability

Assumption can be described as the prior estimate of the probability as $\theta_1, \theta_2, \ldots, \theta_n$, which can be achieved from the historical data, and the prior mean $\overline{\theta}$ or the prior variation S_θ^2 also can be calculated as the following Eq(8,9):

$$E(\theta) = \overline{\theta} = \frac{1}{n} \sum_{i=1}^{n} \theta_i \quad (8)$$

$$Var(\theta) = S_\theta^{\ 2} = \frac{1}{n-1} \sum_{i=1}^{n} (\theta_i - \overline{\theta})^2 \quad (9)$$

Furthermore, its parameters shall conform such student distribution as the following Eq (10):

$$\theta_{U,L} = \overline{\theta} \pm t_{(n-1)} \frac{S_\theta}{\sqrt{n-1}} \quad (10)$$

The parameter θ has its prior distribution in accordance with the following Eq.(11):

$$\pi(\theta) = \frac{1}{\beta(a,b)} \theta^{a-1} (1-\theta)^{b-1} \quad (11)$$

In the Bayesian reasoning, frequency distributions need to converted into PDs for use. Since a failure frequency, θ, in the maritime assessments is well expressed in terms of per vessel operating year, the overall θ values can be considered as their failure rate(mean time between failure), λ, value. If the failure were to follow an exponential distribution, then an equivalent probability value, $P(t)$, for a failure state for the vessel's operational life expectancy, t, is given by the Eq(12):

$$\begin{cases} \pi(\theta) \propto \beta(\hat{a}, \hat{b}) \\ P(t) = 1 - e^{-\lambda t}, \lambda \in [\hat{\theta}_L, \hat{\theta}_U] \end{cases}$$

(12)

VI. PROPOSED RISK ASSESSMENT OF SHIP OPERATION: A CASE

Due to the changes of larger tonnage and faster speed of the modern ships, the increasingly heavy traffic density and the limitation of the fairways, the risk for piloting a ship in Shanghai Harbour is getting much higher than before. As the ship pilotage has the fundamental function for promoting and speeding-up the ship navigation and cargo operation in the harbour, the successful and safety pilotage in Shanghai Harbour has been paid great attention by the authority of the national maritime safety administration and maritime circles in China[9]. For the successful conduct of PRA research projects, the working group had identified the aims, range and contents of the research. In consideration of the practical needs and situation, it also made the detailed research plan by using the method of the PRA.

A. Analysis of Risks on HOF-based Ship Operation in Harbour

The pilotage of ships in harbour is one of the most important components in ship operation safety. A certain hazard in a ship traffic system has resulted in a ship accident, which, in general, can be classified into the traffic accident such as collision, contact, standing, disenable etc. In terms of the HOFs involved in this component, it ought to take livewares, hardware, software and environment with their corresponding elements into account. The probability influence diagram can be useful for the demonstration of modeling and reasoning. All features in the probability influence diagram can be discrete and independent. the probability chart above can be converted to a Bayesian network topology program, as shown in Fig. 3.

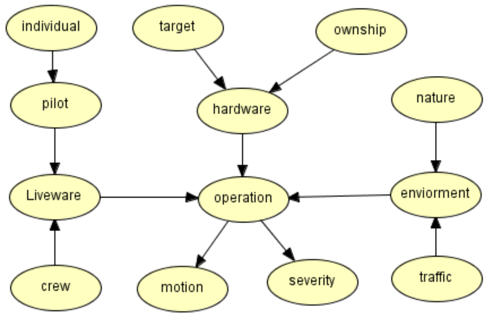

Fig 3 Visual Bayesian Network for HOF-based system of ship operation

B. *Evaluation of Risks on HOF-based Ship Operation in Harbour*

Through the processed data and information from the risk distribution and the analysis of the status of the pilotage operation, the various risk levels could be illustrated with the relevant ranks of risk in different pilotage areas.

Among the areas with the pilotage risks of navigation, the highest one is from No.101 to 107 light buoy, and it occupied 24.1% of the total risk.The second one is from No.107 to 114 light buoy107 which occupied 18.4% of the total risk and the third one is from Yuanyuansha to Wusongkou light buoy which occupied 15.8% of the total risk. These three areas cover 58.3% of the total risks in Shanghai Harbour.

If clarifying the risk frequency into the four levels as frequent, reasonable probable, remote and extremely remote, and dividing the risk consequence into another four levels as catastrophic, major, minor and insignificant with 7 sub-levels, it can be established 10 indexes then it can be indicated as R_2 to R_{11}[6]. On the basis of the analyses, it could be determined that the ship pilotage risk in Shanghai Harbor was within the level of "As Low As Reasonably Practical (ALARP)" according to Generic Model in ship navigation. Taking the operational conditions and operational statuses into account, the risk distribution of the pilotage in Shanghai harbor applying in generic risk model is shown in Table 1. As it indicated that the higher risk ranking Index value 7 was four categories related to such areas as Buoy NO:101＃-107＃, Buoy NO 107＃-114＃,Yuanyuansha to Wusongkou and Wusongkou to Liuhekou while the operational statuses of piloted ship is navigating [6].

TABLE.1
RANKING AND CONSTRUCTING OF RISKS OF PILOTAGE IN SHANGHAI HARBOUR

NO:	Items	Underway	Berthing	Unberthing	Unberthing while swing	Berthing while swing	Swing	Anchoring	Mooring	Unmooring	Alongside another ship
1	Roadstead							$F_1S_2(R_3)$			$F_1S_1(R_2)$
2	Yangzi river Deep channel	$F_1S_3(R_4)$									
3	North Branch to Yuanyuansha	$F_1S_3(R_4)$	$F_1S_1(R_2)$	$F_1S_1(R_2)$				$F_1S_2(R_3)$			
4	Yuanyuansha to Wusongkou	$F_2S_5(R_7)$	$F_1S_4(R_5)$		$F_1S_2(R_3)$		$F_1S_1(R_3)$	$F_1S_1(R_3)$		$F_1S_1(R_2)$	
5	South branch channel	$F_1S_4(R_5)$									
6	Wusongkou to Liuhekou	$F_2S_5(R_7)$	$F_1S_2(R_3)$								
7	Wusongkou to Baosan	$F_2S_4(R_6)$	$F_1S_3(R_4)$	$F_1S_1(R_2)$	$F_1S_1(R_2)$	$F_1S_1(R_2)$					
8	Chongming area	$F_1S_2(R_3)$									
9	Buoy 101＃ to Buoy 107＃	$F_3S_4(R_7)$	$F_2S_4(R_6)$	$F_1S_3(R_4)$	$F_1S_4(R_5)$	$F_1S_1(R_2)$	$F_1S_3(R_4)$			$F_1S_1(R_2)$	
10	Buoy 107＃ to Buoy 114＃	$F_3S_4(R_7)$	$F_1S_3(R_4)$	$F_1S_1(R_2)$	$F_2S_3(R_5)$		$F_1S_2(R_3)$		$F_1S_1(R_2)$	$F_1S_1(R_2)$	$F_1S_1(R_2)$
11	Buoy 114 ＃ to Longhua	$F_2S_4(R_6)$	$F_1S_3(R_4)$	$F_1S_1(R_2)$	$F_1S_3(R_4)$		$F_1S_2(R_3)$	$F_1S_1(R_2)$			
12	Longhua to limmit	$F_2S_4(R_6)$	$F_1S_1(R_2)$		$F_1S_2(R_3)$		$F_1S_2(R_3)$			$F_1S_1(R_2)$	
13	Jinsan harbour				$F_1S_1(R_2)$				$F_1S_1(R_2)$		
14	Lvhuasan anchorage		$F_1S_1(R_2)$					$F_1S_2(R_3)$			$F_1S_1(R_2)$

C. *Predication of Risks on HOF-based Ship Operation in Harbour*

The probability of ship voyage operation can be conducted on the basis of the ship transportation data in recent years. For instance, Table 2 is a demonstration of the recent ship accidents of a certain ship pilot station. The information describes the probability $\theta/1000$ of k accidents in n ship summary activity.

TABLE2
THE ACCIDENT SITUATION FOR SHIP PILOTAGE IN A SHANGHAI HARBOUR

NO.	n_i	k_i	$\theta/1000$
1	75	19774	3.7929
2	44	20736	2.1219
3	26	20510	1.2677
4	28	20940	1.3372
5	31	24602	1.2601
6	31	28082	1.1039
7	51	30884	1.6513
8	44	35832	1.2280
9	82	40985	2.0007
10	53	45287	1.1703
11	47	51330	0.9156
12	57	54945	1.0374

According to the Eq (8,9,10), the results(see fig 4) can be achieved as the following:

$$\begin{cases}\theta_L = \bar{\theta} - t_{n-1}\dfrac{S_\theta}{\sqrt{n-1}} = 0.00114 \\ \theta_U = \bar{\theta} + t_{n-1}\dfrac{S_\theta}{\sqrt{n-1}} = 0.00200\end{cases} \quad (13)$$

But like this the estimation interval of likelihood is rather open, and the sensitivity is so low. Therefore, the Bayesian interval estimation can be obtained as the Eq (14) taken the Eq (11) and (12), which can improve the sensitivity of predication(See fig 4).

$$\begin{cases}\hat{\theta}_L = \beta(\dfrac{\alpha}{2}, \hat{a}+k, \hat{b}+n-k) = 0.00133 \\ \hat{\theta}_U = \beta(1-\dfrac{\alpha}{2}, \hat{a}+k, \hat{b}+n-k) = 0.00156\end{cases} \quad (14)$$

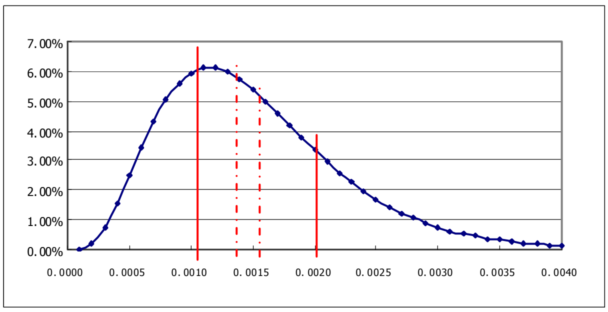

Fig .4 Visual Bayesian Predication of ship pilot accident ratio

Furthermore, the predication of accident ratio can be obtained as the abovementioned. The Bayesian reasoning shall be taken as the following Eq(15) when accident ratio is 1.4‰ and ship activities is 780.

$$P(t = 780) = 1 - e^{-\lambda t} = 1 - e^{-0.0014*780} = 0.68 \quad (15)$$

According the abovementioned computing approach, the probability of each basic factor in ship operation system can be obtained, and the Bayesian network reasoning can be showing as the fig 5.

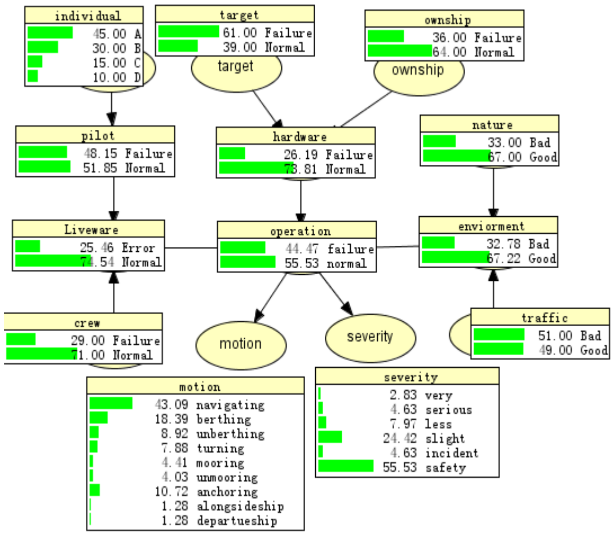

Fig 5 BN model Reasoning for HOF-based system of ship operation

D. Risks control option on HOF-based Ship Operation in Harbour

The results [10,11] of the risk assessment indicate that there are some specific dangerous navigation areas in Shanghai Harbour due to the particular environmental factors. In order to control the serious risks in the vicinity of Wusongkou, the researchers suggested adjusting the time for the berthing and unberthing of the piloted vessels in order to avoid the congested navigation situation (See fig 6).

In addition, to enhance the control of the navigation and operation of the piloted vessels, the way of the on-site commanding by the administrators should be adopted. At the same time, the researchers put forward some suggestions to set up the precautionary areas and strictly control the speed and position of the ships navigating from the Yuanyuansa to Wusongkou, especially to control the encountered situation between the vessels for avoiding and reducing the natural and traffic risks in this area, with tide raising and ebbing during a day period.

To strictly monitor the ships' safety pioltage, it is necessary to raise the management level by using advanced technology and control system for the ship safety pilotage. The researchers also advised the station administration to establish an integrated monitoring system (including the Electronic Chart Display System (ECDIS) and Automatic Identification system (AIS) which can cover all pilotage waters in this Harbour. This integrated system can be used for enhancing the control ability and specially ensuring the safety pilotage in the specific important and dangerous areas of the harbour.

As the most important contributing factor of pilotage accidents is the human effect according to the results of the research, and the researchers advised the pilots and relevant administrators to pay full attention to this practical situation and find out what kinds of the concept, attitude and behaviour of the pilots will cause the pilotage accidents. Organizing analysis and discussing about the various pilotage accidents or holding the particular workshop or seminars for the specific topics and cases dealing with the safety pilotage can carry these out.

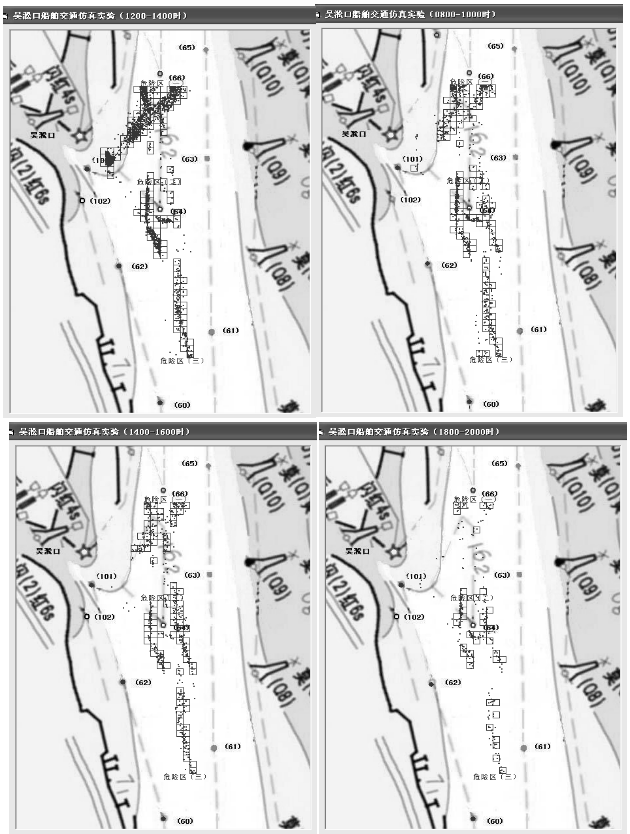

Fig.6 Simulations and Control of danger area in the vicinity of Wusongkou with tide changes[top left figure is showing H_{-7}- H_{-5} the situation of encountered ships during the period of 7h to 5h before high tide time, bottom left is H_{-3}- H_{-1}, top right is H_{-1}- H_{+1}, bottom right is H_{+2}- H_{+4}]

V. CONCLUSION

A proposed risk assessment approach could be used to model the components that affect reliability and how they interact [12]. Besides, the graphical nature of a Bayesian network makes the model intuitive for users to understand. The process of performing Bayesian updating involves selecting a prior distribution, calculating the normalizing constant, formulating the frequency function, and then calculating the posterior distribution. The frequency function incorporates the objective information, while the prior distribution can include subjective information known about the distributions of the model parameters. Therefore, the posterior distribution incorporates both the objective and the subjective information into the distributions of the model parameters. Hence, PRA bases on Bayesian method are well suited for modeling maritime safety-critical systems prediction and risk analysis[7,8]. The results from the case studies, as well as other renewed research work, indicate the BNs give a sound and transparent approach to operational system risk. [11,12]

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