A PETRI NET MODEL FOR A CAUSATION ANALYSIS OF SHIP FOUNDERING

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A ship foundering causation analysis model is developed in this paper adopting the Petri Net method to represent the historical data collected from the China Maritime Safety Administration. The Petri Net model proposed is able to identify critical safety factors and event chains that lead to shipwrecks. As such, this model can provide certain insights for decision making on the prevention of ship foundering. A series of case studies are further carried out for the validation and utilization of the model.

I. INTRODUCTION

The Silk Road Economic Belt and the 21st-century Maritime Silk Road, also known as The Belt and Road is a development strategy and framework, that focuses on connectivity and cooperation among countries primarily between the China and the rest of Europe. Along with the implementation of China's Belt and Road policy, the utilization of waterway transportation has shown an inevitable and steady upward trend. According to the results presented in the Chinese Transportation Development Statistical Bulletin of 2015, inland water transportation (IWT) accounted for the movement of 3.459 billion tons of cargo [1], which catapulted Chinese water transportation into the front ranks, globally speaking. However, given the vigorous expansion of waterway transportation, it is important to note that IWT is also a high-risk industry. In 2015, 212 maritime accidents were recorded. These accidents included collisions, foundering, groundings and oil spills, and the direct economic losses amounted to 349 million yuan [1]. The frequency of accidents has caused the concern from both society and the transport sector, while the studies conducted on IWT economy and management in China thus far have been limited and weak.

With the rapid development of China's water transport industry, maritime security cannot be ignored. Ship capsizing accidents account for 33% of all maritime traffic accidents, according to maritime sector statistics [1]. In addition, the capsizing or foundering ships pose a massive threat to both the people and the property on the ship, because it usually takes only a few minutes for ship to transition from heavily heeled to foundering. Therefore, basic, effective measures should be taken to prevent ships from capsizing.

In view of the different severity levels of damage caused by capsizing accidents, numerous studies have been conducted on such accidents. Kougioumtzoglou [2] developed an approach to determine the capsizing probability of a model ship subjected to non-white noise wave excitations. The reliability of the approach was demonstrated by comparing results with the corresponding Monte Carlo simulation data. Spyrou [3] derived closed-form relationships that characterize a ship's capsize-ability by linking the critical wave-slope, the amount of bias and the damping. Umeda [4] presented experimental records of the capsizing of model ships in following and quartering seas. In addition, Umeda classified the recorded capsizes into four modes, namely 1) broaching, 2) low cycle resonance, 3) stability loss on a wave crest, and 4) bow diving. They discovered the qualitative and quantitative characteristics by using nonlinear dynamics. Huang and Zhu [5] calculated ship capsize probability via a path integration method. Tang and Gu [6] assessed the osculating relations between the phase space flux and ship capsizing via a Melnikov function and phase space flux.

The capsize could eventually be the result of parametric roll [7], which at least has produced much damage to cargo as has been reported at occasions. Large amplitude rolling can be one of the causes of ship flooding [8,9], leading to the total loss. And various progresses have been made in the analysis of this problem probability [10,11,12].These models deal with the roll dynamics of ships in waves and after increasing the roll angle due to increasing roll amplitude in the same conditions. However this is not what happens in reality because ships are operated by ship personnel who will change course or speed to enable the ship going out of the synchronous roll motion once feeling increasing roll angles because of synchronization with the waves. However there might be situations that this has not been possible due to some human or technical failure.

Therefore it is necessary to conduct proper accident investigation which includes the identification of the events that led to the final outcome as well as the influencing factors, to fully understand what happened in an accident. One such approach was developed during the European project CASMET, leading to an accident investigation method [13] that was further developed in a paper [14] which has a taxonomy associated so that the causes can be properly coded in databases [15]. Actually, this is the main approach that was finally adopted in its major aspects by the European Safety Agency (EMSA), where an accident database is kept.

The analysis of the statistics of events and influencing factors may provide the quantitative basis [16] to support the development of more detailed models, like Fault trees [17], or Bayesian Networks [18], that will allow quantification of the probabilities involved.

Various forms and generalizations of Petri Nets have been demonstrated to model security services and access controls over the last few decades. Jure and Miha [19] constructed basic building blocks for gene regulatory networks using PNs. Julvez et al. [20] proposed an optimization-based event-driven control approach applied to a continuous time model based on Petri Nets. Aitouche and Hayat [21] developed an agent in order to solve waterway traffic congestion problems by means of colored Petri Nets.

Though the Petri Net method has been widely acknowledged as one of the most effective methods of fault diagnosis and workflow management, PN is also a promising method that can be used in accident causation analyses, in order to enhance navigational safety. From this perspective, a ship foundering causation analysis model is developed in this paper on the basis of the Petri Net method combined with historical data collected from the China Maritime Safety Administration. The accident data is then placed into the Petri Net tool to verify the correctness of the proposed model. The proposed Petri Net model is able to identify critical safety factors and event chains that lead to shipwrecks, which in turn could provide certain insights for decision making to prevent ship foundering accidents.

This paper is structured as follows. In Section 2, the Petri Net theory used to demonstrate the proposed model is introduced. Modelling ideas and the capsized ship model are explained in Section 3. Section 4 focuses on the case studies and conclusions are given in Section 5.

II. PETRI NET METHOD

The Petri Net theory was first put forward by Carl Adam’s publications in 1962 and PN was gradually accepted to be a powerful graphical and mathematical tool used to describe systems and their actions. The behavior characteristics of a system can be analyzed relatively easily by using Petri Nets [22].

A Petri Net is a graph, consisting of places transitions and arcs. Arcs run from a place to a transition or vice versa, but never between places or between transitions. The places from which an arc runs to a transition are called the input places of the transition; the places to which arcs run from a transition are the output of the transition. Graphically, places in a Petri Net may contain a discrete number of marks called tokens. Any distribution of tokens over places will represent a configuration of the net called a marking. When the transition fires, it consumes the required input tokens and creates tokens in its output places. A firing is atomic, i.e. a single non-interruptible step. Unless an execution policy is defined, the execution of a Petri net is non-deterministic. When multiple transitions are enabled at the same time, any one of them may fire. Since firing is non-deterministic and multiple tokens may be present anywhere in the net (even in the same place), a Petri Net is well suited for modeling the concurrent behavior of distributed systems.

In general, the symbol “○” is used to represent a place, “□” represents a transition, “.” represents a token and “→” is a directed arc. Figure 1 shows a simple process Petri model.

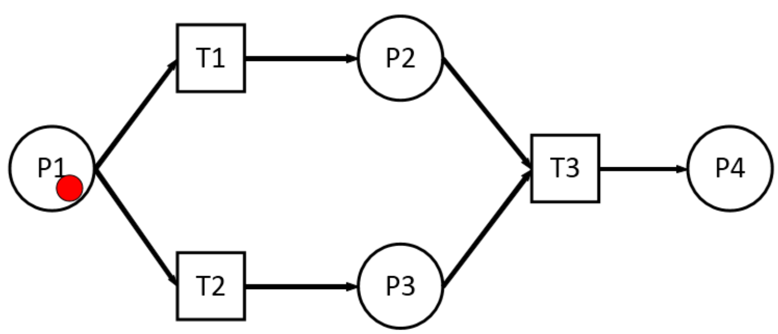

Fig. 1. Example of a standard Petri Net

III. MODEL

III.A. Modeling Ideas

The Waterway Transportation system is complex and dynamic system with various factors influencing each other and thereby increasing the difficulty of assessing navigational risks [23]. Waterway accidents can be caused by factors ranging from the natural conditions to the ship and the crew, and even the shipping company's management and administration. Four main aspects of the Inland Waterway Transportation System, namely, 1) human, 2) vessel, 3) environment and 4) management, have been identified as potentially responsible for accidents, based on expert judgment and previous studies [24].

(1) Human factors can include: incompetent crew, wrong decision, navigating while fatigued, inappropriate velocity, lack of safety consciousness, insensitivity to conditions, poor operation of the vessel, and so on. More than 80% of accidents are caused by human factors, according to the statistics [1]. In light of this fact, the emphasis on the quality of the crew should be increased, in order to ensure and improve water safety.

(2) Factors relating to the vessel itself can include: unserviceable or poorly serviced, structural deficiencies, lack of stability, improper loading of goods, illegal refit, and so on. The ship's structural problems alone can be a direct factor leading to an accident.

(3) Environment issues include: hydrological environment, weather (natural environment), density of traffic flow, channel order (navigation environment), and so on. Environmental factors are almost the main factor in an accident where the ship capsizes.

(4) Management problems include: shipping companies having insufficient safety procedures, crew lacking professional training, overloading, conducting illegal transport loads and goods, and so on. Achieving greater efficiency and safety will rely on effective management. This finding is based on the specific survey conducted for this paper, which includes details of the waterway and vessel traffic, among others.

III.B. Capsized Ship Model

The model proposed in this paper is based on the research of an accident report. Considering the four factors of human, ship, environment and management, and based on the elements of the current accident causation theory, a network modeling the capsizing ship accident is constructed using Petri Nets. Based on the actual accident, the constructed model produces the rules. These rules are derived from the statistics of the accident reports and are given as the definition of each place, as: shown in Figure 2 and Table I:

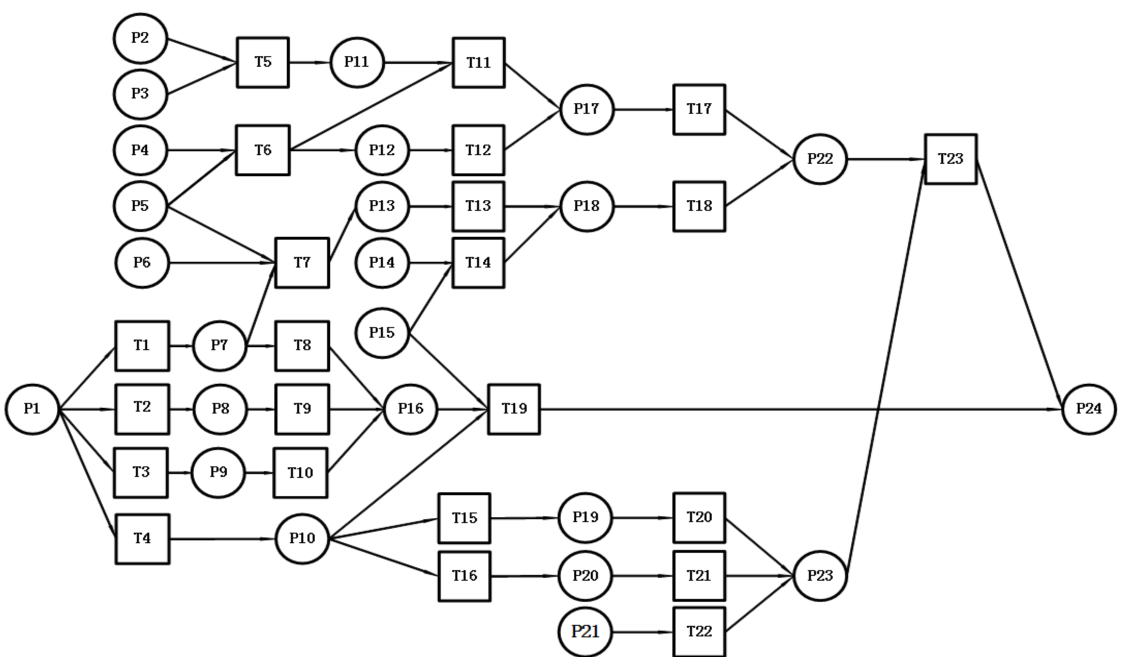

Fig. 2. Ship Capsizing Model based on Petri Nets

TABLE I. Implication of Place

Place	Implication	Place	Implication
P1	Insufficient safety supervision of the shipping companies	P13	Ship damage
P2	Cabin-fire	P14	Hatch cover opened
P3	Improper fire-fighting	P15	Heavy weather
P4	Improper loading of goods	P16	Unserviceable ship
P5	Gale, storm waves	P17	Unstable ship
P6	Tough navigation environment	P18	Bilging
P7	Bad ship stability	P19	Crew -- lack of professional training
P8	Illegally modified	P20	Incompetent crew
P9	Overloaded, illegal transportation	P21	Lack of safety consciousness, insensitive
P10	Human factors	P22	Ship heel
P11	Water for fire-fighting left in the cabin	P23	Incorrect operation
P12	Cargo shifting	P24	Ship capsizes

Referring to the relevant information in the report on the accident, the definition of each node in the model is explained as follows:

(1) The insufficient safety supervision of the shipping companies (P1) :

For each specific incident, it is difficult to hold the shipping company's management accountable. In reality, however, the shipping company's poor management and lack of attention to safety, facilitates the happening of accidents. The management is ultimately responsible for factors such as incompetent sailors, poor or non-existent documentation and implementation of crew training. The lack of this documentation and training hides the reasons for the accident. The ship was on the stage of the cause of the accident when it set out on a voyage under the deficient safety supervision of the shipping companies. Therefore, the model should start with the shipping company's management.

(2) Cabin fire (P2), improper fire-fighting (P3), water for fire-fighting left in the cabin (P11) :

The increase of ship fire accidents over the years presents a great danger to the safety of ships, cargo and even the crew on board. Cabin fire is a common and significant risk accident factor in ships. Cabin fires not only propagate quickly, but also are unexpected and powerfully destructive. If the water intended for fire-fighting is not disposed properly and is left in the cabins after the crew puts out a fire, a ship can overturn in severe weather.

(3) Improper loading of goods (P4) :

There are too many accidents occurred in transit because the cargo was not properly secured. If the ship experiences gale-force winds or storm seas, unsecured cargo can easily move, which can then lead to an accident. Under no circumstances should cargo loading or ballasting ever be carried out in such a manner that the ship's stability is threatened.

(4) Gale, storm waves (P5) :

The heavy weather often affects the crew's ability to control the ship, which in turn can lead to an accident, though the natural environment is not usually the direct root cause of accidents. Extreme weather conditions not only affect the crew's visibility, but also cause a lot of difficulties in controlling the ship. In addition, extreme weather will make it very difficult for the master to judge the direction of the wind accurately and keep the ship on a steady course. In addition, poor visibility can lead to navigators failing to avoid trouble through measures such as heading the ship against the waves or the wind [25,26]. This chain reaction can then make the crew fail to implement other possible rescue methods or take other measures that may benefit the escape. At the same time, bad weather makes it very difficult for the crew to save themselves, and makes the maritime search and the rescue ineffective [27].

(5) Tough navigation environment (P6) :

With the ongoing development of the technology, more complicated ships and bridges are being built, which makes the navigation environment more complex and difficult. Constant changes in the channels make it difficult for the captain to choose an appropriate approach channel with fewer obstacles or hidden reefs. When a ship sails in a narrow or constantly-changing channel, ship grounding can happen. Ship grounding accidents in extreme weather may develop into disasters as ship hull damage.

(6) Bad ship stability (P7), Illegally modified (P8) :

A ship's stability is fundamental to the safety of its crew, its cargo and the environment [28]. If the ship's stability (centre of gravity) is too high or too low or both, the ship's navigational safety is not guaranteed. Thus, in terms of water transportation safety, ships should have moderate stability. Illegally modified a ship can seriously affect the ship's stability. Such ships frequently can't resist gale-force winds and heavy seas. This is why refits of ships are strictly controlled by maritime sector administrations.

(7) Overloaded, illegal transportation (P9):

Domestic ship management companies are still imperfect, not only from an operational perspective, but also in terms of the low level of management. Ship management is frequently conducted on a laissez-faire basis, and the shipmaster is often driven solely by economic benefits. Overloading and transporting illegal goods is a common situation, because ship owners ignore the safety regulations.

(8) Human factors (P10), crew -- lack of professional training (P19), incompetent crew (P20):

Too many accidents are caused by human factors, as directly shown by accident statistics. Some local towns or enterprises, driven by economic interests ignore the crew's safety training. A sailor with poor professional skills, a lack of safety consciousness and operation under stress conditions, can't meet the safety requirements of waterway transportation. Crews who have not been professionally trained can't make the right choice when their ship is in danger. They could also have a negative effect on rescue efforts. These factors combined can easily lead to accidents.

(9) Ship damage (P13), hatch cover opened (P14):

As an important part of the ship, the hatch cover plays a critical role in keeping sea water away from the ship's cargo and passengers. The hatch directly influences the safety of the cargo and the ship itself during transportation. However, crews will sometimes leave the hatch cover open. In this case, water can easily enter the cabin through the open hatch or through any break in the hull in heavy weather. Flooding of the cabins can then lead directly to a shipwreck.

(10) Lack of safety consciousness, insensitivity (P21):

Even a professional crew, in certain psychological conditions (such as when lacking safety consciousness, or crews who are unnecessarily reckless and bold) may also make mistakes. Studies have found that a number of traffic accidents are directly related to the crew's emotional state. Therefore, not only the crew's professional skills, but also their psychological qualities, should be given attention.

IV. CASE STUDY

IV.A. Accident Data

Based on the proposed Petri Net model, safety critical factors and event chains that lead to capsized accident can be analyzed, which would provide certain insights for decision making on preventing ships from capsizing. A few cases in the Yangtze River are shown in this section to demonstrate how to use Petri Net to analyze the capsized accident in the longest river in China.

According to the proposed Petri Net model, the factors which caused the ship capsized accidents will be found by analyzing the accident report [29]. If the factors match to the places in the proposed model, one token will be created and put in to the corresponding places. When the transition fires, it consumes the required input tokens and creates tokens in its output places till the token can't remove from the places or none transition can be activated. If the P24 has one or more token finally which means the ship will capsize. The 28 capsized accidents which were collected by the Ministry of Transport of the People's Republic of China [29] have been verified, and the verification results are shown in Table II:

TABLE II. The 28 capsizing case verification results and real accident outcome

No.	Ship	Input	Model Results	Real Outcome
1	Sheng Jia 16	P_1, P_4, P_5, P_9, P_{12}, P_{23}	Capsized	Capsized
2	Hung Cuong 168	P_4, P_5, P_{12}, P_{23}	Capsized	Capsized
3	Tai He 9	P_1, P_{14}, P_{15}, P_{21}	Capsized	Capsized
4	Non-transport ship	P_1, P_7, P_9, P_{10}, P_{20}	Capsized	Capsized
5	Bin Hai 103	P_5, P_6, P_7, P_{13}, P_{23}	Capsized	Capsized
6	Fu Hang Tuo 268	P_1, P_{14}, P_{15}, P_{23}	Capsized	Capsized
7	Shun Qiang 1	P_4, P_5, P_{12}, P_{21}, P_{23}	Capsized	Capsized
8	Ming Yang Zhou 178	P_1, P_5, P_9, P_{10}, P_{15}, P_{20}	Capsized	Capsized
9	An Jing	P_4, P_5, P_{14}, P_{15}, P_{18}, P_{21}	Capsized	Capsized
10	Xian Feng Hai 1	P_4, P_5, P_{12}, P_{23}	Capsized	Capsized
11	Liao Pu Yun 777	P_1, P_4, P_7, P_9, P_{12}, P_{23}	Capsized	Capsized
12	Chi Bi 3	P_9, P_{10}, P_{15}, P_{20}, P_{21}	Capsized	Capsized
13	Hua Yuan Shun 18	P_1, P_5, P_7, P_{14}, P_{18}, P_{23}	Capsized	Capsized
14	Shun Da 2	P_1, P_5, P_6, P_7, P_{13}, P_{14}, P_{18}, P_{23}	Capsized	Capsized
15	Sa He Kou	P_{21}, P_{23}	Non-capsized	Capsized

No.	Ship	Input	Model Results	Real Outcome
16	Jia Ding Guan	P_5, P_6, P_7, P_{13}, P_{23}	Capsized	Capsized
17	Hua Ding San	P_2, P_9	Non-capsized	Capsized
18	San Hang Zhuang 4	P_{14}, P_{15}, P_{21}, P_{23}	Capsized	Capsized
19	Fei Yun Lin	P_5, P_6, P_7, P_{13}, P_{14}, P_{18}, P_{23}	Capsized	Capsized
20	Su Se 18	P_6, P_{14}, P_{15}, P_{23}	Capsized	Capsized
21	Xia Chuan 1	P_5, P_6, P_7	Non-capsized	Capsized
22	Zhe zhou 606	P_1, P_{14}, P_{15}, P_{18}, P_{20}, P_{23}	Capsized	Capsized
23	Da Shun	P_2, P_3, P_4, P_9, P_{11}, P_{23}	Capsized	Capsized
24	Sheng Lu	P_2, P_3, P_4, P_5, P_{11}, P_{12}, P_{23}	Capsized	Capsized
25	Jia Yu	P_5, P_6, P_7, P_{23}	Capsized	Capsized
26	Jing Shui Quan	P_5, P_6, P_7, P_{13}, P_{21}	Capsized	Capsized
27	Chuanjiang An Du 0016	P_1, P_6, P_{21}, P_{22}, P_{23}	Capsized	Capsized
28	Eastern Star	P_1, P_5, P_8, P_{12}, P_{14}, P_{15}, P_{21}, P_{22}, P_{23}	Capsized	Capsized

IV.B. Discussions

As per the result of Table 2, every factor that appeared in the accident will be reflected as the places in the model. It also shows the 28 accident verification results, and only three accidents (Case No.15,17,21) of them do not conform to the model. As such, this model can provide certain insights for decision making on the prevention of ship foundering.

For Case No.28, the Eastern Star's accident report showed the ship was caught in a storm and the storm was the likely cause of the capsizing. Secondly, the Eastern Star's stability gradually dropped after each of the three modifications, making the vessel unable to withstand heavy weather. Meanwhile, the captain and the mate on duty were not cautious enough when they encountered the extreme weather; they were then unable to make the right choices to cope with the crisis. Therefore, the P1, P5, P8, P12, P14, P15, P21, P22 and P23 exist in the proposed model and were given a token. That fired the T2, T12, T14, T22, T23 so the tokens in the places were removing to the P24 finally which means the Eastern Star would sink according to the model. The verification result of the Eastern Star conforms to what actually happened in the accident.

For Case No. 15, it's easy to discover that this vessel's accident happened in an open port with a light breeze and waves. The Sa He Kou sank on because the special requirements for the caisson floating were ignored. Also, the crew did not strictly abide by the security operation regulations, and both the ship's crew and the cargo lacked the necessary coordination. These were the essential reasons for the accident. From the above facts, we see that negligence, human fault and the crew's lack of skill all contributed to this accident. Therefore, P21 and P23 exist in this model. However, the firing of T23 consists of removing a token from P22, P23 which doesn't meet the model's requirements.

For Case No. 17, the Hua Ding San's accident report shows there was fire and that illegal transport business was being conducted. After the ship went on fire, the metal distortion caused by the fire's high temperature caused the hatch not to seal properly. Due to this hatch distortion, the ship started to flood, which ultimately caused the ship to capsize. This chain of events still conforms to the codes in our model, although with fewer of the proposed factors. Therefore, P2 and P9 exist in the model, but they don't meet the demand that T23 could trigger.

For Case No. 21, the Xia Chuan accident report shows that the key factor which led to the ship sinking was heavy weather, and it caused damage to the ship's hull. Nobody was on the boat when the accident happened. In short, the accident was caused by bad weather and not by human factors. Therefore, P5, P6, and P7 exist in the model, but they don't meet the demand that T23 could trigger.

IV.C. Model Application

In this section, the proposed Petri Net model was used to analyze the accident causes. With reference to Table II and Figure 2, the chain of events of the capsizing accidents can be summed up in Table III.

TABLE III. The 28 capsizing case verification results and real accident outcome

No.	Event chain	Times	Rank
1	T_1/ T_2/T_3→T_8/T_9/T_{10}→T_{19}	2	4
2	T_1→T_7→T_{13}→T_{18}→T_{23}	2	4
3	T_4→T_{19}	1	5
4	T_4→T_{15}/T_{16}→T_{20}/T_{21}→T_{23}	1	5
5	T_5→T_{11}→T_{17}→T_{23}	2	4

No.	Event chain	Times	Rank
6	$T_6 \to T_{12} \to T_{17} \to T_{23}$	6	2
7	$T_7 \to T_{13} \to T_{18} \to T_{23}$	5	3
8	$T_{14} \to T_{18} \to T_{23}$	8	1
9	$T_{22} \to T_{23}$	5	3

These suggestions are offered in terms of the model:

During the past 20 years, ships sinking for the fact that the hatch cover was open, accounted for 29% of all ship capsizing accidents, according to maritime sector statistics. The design of the boat hatches must take into consideration a vessel's sustainability in high winds. It is suggested that the maritime sector should change the marine rules and improve ship hatch covers to strengthen their sealing properties. Otherwise, it could also be possible that the authorities could reduce the classification of those vessels on the basis of the vessels' sustainability in winds. Vessels with inadequate hatches could be restricted to areas of operation where the safety of such boats would be ensured.

It can be seen that most accidents happen in bad weather, but the natural environment is not the direct root that causes most accidents. However, it is true that the heavy weather and a difficult navigation environment often affect the crew's ability to control the ship, which in turn leads to accidents. Therefore, it is necessary to enhance the ability to predict adverse weather, to reduce the time it takes to transmit traffic information and to ensure accurate reporting.

The model has shown that seamen with bad professional skills, a lack of safety consciousness and who are operating under the strain of capacity cannot meet the requirements of safe waterway transportation. Through analyzing these problems, this paper emphasizes the urgency and importance of raising the professional level and quality of maritime crews. Measures should also be taken to enhance the captain's capacity to respond to emergencies and thus help ensure the safety of waterway transportation.

V. CONCLUSIONS

In this paper, the Petri Net method is applied to analyze the critical safety factors and chains of events that lead to shipwrecks, which have been received increasing attention in recent years. Efforts in conducting a case study have been made based on historical data collected from the China Maritime Safety Administration, and this data demonstrates the appropriation of the model. The method proposed is further demonstrated and validated in the case study by analyzing the accident reports [29]. In this study, by using the Petri Net method, we were able to review accidents and find the key factors which led to ships capsizing. Therefore, the results of this study provide certain insights for decision making on the prevention of ship foundering and thus enhancing the safety of the shipping industry.

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