Article

A Hybrid Approach for Quantitative Analysis of Fire Hazards in Enclosed Vehicle Spaces on Ro-ro Passenger Ships

Junzhong Bao*, Zhijie Bian, Bitong Li, Yan Li and Yuguang Gong

Dalian Maritime University (DMU)

* Correspondence: baojunzhong@hotmail.com

Abstract: This study probes the probabilistic features of major fire hazards in enclosed spaces to establish their importance to the occurrence of fires onboard ro-ro passenger ships and in turn to raise effective operational countermeasures. Distinct from the previous studies, the present research employs Bayesian Network (BN) analysis to determine the probabilities of fire hazards more effectively. The findings of the research include five critical basic events (BE) identified namely, vehicle engine fire (fuel system fault), vehicle electric fire (electrical equipment defect or short circuit), used car electrical fire, reefer units electrical fire (electrical appliances defects or short circuit), and cargo spontaneous combustion. Additionally, the risk of fire for lithium - ion battery powered vehicles is also highlighted in the process of BN analysis, which prompts the authors to propose preventive measures for mitigating the possibility of fire occurrence on this type of electric vehicles. It is hoped that these measures can be essential justifications for establishing relevant rules regarding carrying LIB vehicles in enclosed spaces on international level.

Keywords: Risk analysis; Fire hazards; Bayesian network; Ro-ro spaces

1. Introduction

Ro-ro passenger ships (hereafter Ro-pax) on short-sea routes, have been extensively utilized in marine transportation with significant commercial success achieved[1]. (IMO, 2022) But disturbing accidents, in particular, fire /explosions ignited from cargo spaces of Ro-Pax have made safety issues a prominent concern.

The high fire risks on Ro-pax may be partly connected to their unique structural features, such as large and open garage space(s) for vehicles to roll on or roll off the ferry, which makes confining a fire to its place of origin more difficult. (McGregor et al., 2021) [2] Consequently, the fire starting from an enclosed cargo deck may extend to other areas affecting passengers and crew, leading to more potential severe consequences.[3] (IMO, 2016) And reportedly, the fire incidents on Ro-pax is not diminishing. (EMSA)[4] (IUMI, 2017). Besides, ~~f~~erries have particular risks from the cargo they carry such as cars, lorries and refrigerated containers which all contain combustible materials and therefore, have their fire hazards which the ship's crew cannot easily control. (McGregor et al., 2021)

The fire accident on Ro-pax Zhonghua Fuqiang on April 19, 2021, is one of the typical casualties sounding the alarm that the root causes of fire may not have been identified in previous studies. (China MSA, 2021)[5] Similarly, though with no crew injury, the fire aboard the ro-ro cargo vessel Höegh Xiamen on June 4, 2020, caused nine fire-fighters injury[6]. (The Maritime Executive, 2022) These grave accidents highlight that fire casualty in vehicle spaces of Ro-pax entails further in-depth examination.

The analysis studies on more recent fire accidents (DNV, 2016)[7] (EMSA, 2019)[8] (RISE, 2021) [9] show that the number of fires on ro-ro decks remains high. Therefore, it is paramount to investigate root causes of fires on ro-ro decks using BN methods.

In this study, firstly, typical causality chains and the common fire causes are identified. This is achieved by the literature review, reexamining selected investigation reports of fire accidents in enclosed spaces onboard Ro-pax. Secondly, the techniques of BN are applied to underline the priority of causality chains. Thirdly, practically feasible solutions are proposed to reduce the high profile hazards of fires in enclosed spaces.

Our study focuses on fire hazards that occur in the enclosed vehicle spaces of Ro-pax, and fires occurring in other spaces aboard those ships are excluded. All the fire accidents surveyed in this study, are categorized as serious accidents as per established criteria (IMO, 2008; MOT of China, 2021; RISE, 2021). [10] [11] Further, the cost and benefit analysis of risk control options proposed are not scoped in this study, neither are emergency response and fire containment issues.

Quantitative risk analysis for the fire hazards in enclosed spaces is performed, and weighted causal chains of fires are prioritized. The outcome of this study can be referenced to by competent authorities in developing administrative regulations for safe vehicle transport at sea. In addition, owners and operators of ro-ro shipping industry can utilize the results when formulating a plan for identifying key failures of fire causes on board Ro-pax as well as developing measures to improve fire safety in routine operations.

The remainder of this paper proceeds as follows. Section 2 presents a literature review of current studies and their limitations. Section 3 and Section 4 layout the methodology and calculation process applied in this study. Section 5 discusses and analyses the prioritized factors of fire causes and their corresponding effective risk control options (RCOs). Section 6 presents the conclusion and discussion.

2. Literature Review

2.1. Current studies on fires in vehicle spaces on Ro-pax

Several prominent previous risk analysis studies focus on generic risk analysis of Ro-pax fires were primarily performed in accordance with the FSA Guidelines issued by IMO (IMO, 2007).[12] The pioneering studies were conducted by DNV and Denmark using Event Trees (ET) models. (DNV, 1996)[13](IMO, 2008)[14] (IMO, 2016)[15] Two successive studies (FIRESAFE I in 2016 and FIRESAFE II in 2017) were commissioned by EMSA, with the former focusing on electrical fire as ignition risk and the fire extinguishing failure in ro-ro spaces, while the latter on subject matters beyond the coverage of the former. However to the best knowledge of the authors of this paper, it is yet a qualitative and semi-quantitative risk analysis (EMSA, 2016).

Following a study finalized in 2005, DNV GL carried out a follow-up study to examine subsequent fire accidents between 2005 and 2016 to improve fire safety in daily operations from the perspectives of owners and operators through an investigation of common causes of fires in ro-ro spaces. And those common causes or ignition sources of fires identified have been referenced in this study. (IMO, 2012)[16](DNV GL, 2016) (RISE, 2020) [17](RISE, 2021)

The more recent study is the LASHFIRE project where the Failure Mode and Effects Analysis (FMEA) was used to identify sources of fire initiation and hazards worsening consequences of fires in ro-ro spaces, and a list of fire causes, fire origins, failure modes, and safety measures was created. (RISE, 2020)

Apart from those above-mentioned studies conducted by organizational entities, professional scholars also probed into the fire causes for Ro-pax by applying standard risk analysis techniques. Endrina et al. (2018), having reviewed relevant risk analysis studies for the world-wide Ro-pax fleet published by scholars, and using accidents statistics covering the period 2000–2011, performed a comparative study of a risk analysis results for Ro-pax ships operating in the Strait of Gibraltar. (Endrina et al., 2018)[18]

The main causes of fire identified in the previous studies include electrical fault, mechanical failure, thermal reaction, and human error.[19] (USCG, 2020;[20] McGregor et al., 2021; IUMI, 2017; IMO, 2019). Wu et al. (2021) Kwiecinska (2015) (IUMI, 2017) (RISE, 2020). (IMO, 2012)) In this study, fire hazards in ro-ro spaces are classified into 4 streams, including technical failures, which target ship equipment failures and electronic failures leading to vehicle fires; ship cargo hazards, which involve vehicles carried onboard and cargo units loaded on vehicles; vehicles' lasing failures and human factors observed such as vehicle drivers' unsafe behaviors. These streams constitute the four branches of fault tree (FT) framework.

 doi:10.20944/preprints202306.0638.v1

Fire casualty data surveyed in the previous studies addressing fire on Ro-pax are mainly derived from Lloyds Maritime Information Unit database (IHS), British MAIB database, EMCIP and GISIS MCI data, FSI 21/5. (IMO, 2008; IMO, 2012; EMSA, 2015; EMSA, 2016; EMSA, 2018; RISE, 2020) All these databases constitute the principal sources for statistical collection in the present study. Another source of data for this study is from published literature works written by the Chinese scholars or maritime investigation reports issued by Chinese government to record some Ro-pax fire accidents that happened in China in the last 20 years, from 2002 to 2021.

In estimating the occurrence of fire accidents in Ro-pax, RISE (2020) reviewed the previous studies in which outputs come up with the frequencies of fire accidents in ro-ro spaces. Hence, a summary list is produced with the frequencies of fire accidents for various studies (Papanikolaou, et al., 201521; Leroux et al., 2018; IMO, 2008; EMSA, 2018; DNV GL, 2016). Those frequencies of ship year served as an input in identifying hazards in LASHFIRE project (RISE, 2020). In addition, those frequencies can be utilized as a cross reference for the occurrence of top events of event tree for future studies to verify future analysis for fire accidents in Ro-pax studies. The input values to those models applied by previous studies were based on statistics from the historical data, findings of researches, and expert judgement.

2.2. BN in quantitative analysis of ship accidents

In the fields of safety study, a fault tree is used to model the relationship between relevant events and can be applied to both qualitative and quantitative analysis (Antao & Soares, 2006).[22] Fault Tree Analysis (FTA) has also won a place in ship accident analysis. Wang et al. (2013) constructed a fault tree to identify leading basic events and minimal cut sets for fire accidents on a crude oil tanker.[23] Töz et al. (2022) proposed a fault tree model for an empirical study of 62 collision accidents recorded in high profile database over 15 years up to 2020. [24] Ugurlu et al. (2022) used FTA to determine the probability and importance of the primary causes of ship collision accidents. [25]However, there are certain inherent drawbacks relating to the application of conventional FTA; for example, it is impossible to encompass linguistic variables in the failure logic model when handling the uncertainties (Mahmood et al., 2013). To compensate for this limitation, the fuzzy set theory is introduced into the process of FTA.

FTA, as a kind of static analysis instrument, is incapable of updating the status probability (Ugurlu et al., 2022; Ibrahim and Rao, 2019)[26], but a Bayesian Network (BN) is a factorization of a probability distribution along with a directed a cyclic graph (Koski and Noble, 2012). [27] Unlike FTA, BN is created only using expert judgement, factor correlation, or a literature review (Zhang et al., 2019), and cannot determine how failures lead to unwanted events (Lampis and Andrew, 2009). Therefore, the integration of FTA and BN has become a potential solution for obtaining more accurate estimation of probabilities (Khakzad et al., 2011) and it is expected to minimize method-related constraints, a common problem in applying FTA alone (Ugurlu et al., 2022). Several scholars have integrated the FTA into the BN when analyzing ship accidents (Chen et al., 2015; Jia et al., 2018; Wang et al., 2020; Ugurlu et al., 2022). Ugurlu et al. (2022) mapped FTA into a BN and used a dynamic risk analysis methodology to analyze the risks of grounding accidents in 15 years starting from 2005. Wang et al. (2020) used an FTA-BN algorithm to present a framework for identifying critical risk factors for ship fire accidents. Wu et al. (2021) created a data-driven BN model to analyze potential hazards for fire accidents of electric vehicles, which took place in China from 2011 to 2018, and highlighted that charging electric cars transported aboard ships would increase the probability of car fire occurrence. Cenk et al. (2021) applied FTA and a Bayesian network (BN) analysis to establish the risk level by defining the level of relationship among factors, and then evaluated its impact on grounding.[28] Because the occurrence of certain numbers of basic events under FTA may not always be observed or unable to be determined, expert judgement may help determine the probabilities of those basic events.

 doi:10.20944/preprints202306.0638.v1

2.3. Limitations of previous studies

Some previous studies focused on the establishment of high level risk methods where event tree analysis are initiated from a Top Event (TE), while other studies established fault tree analysis focusing on qualitative analysis of the influence of causal chains of fire onboard ships. However, there are insufficient quantitative studies on fault tree analysis of fire accidents in ro-ro spaces, much less are the studies employing BN in risk analysis. This study intends to conduct research with this methodology to delve into the quantitative relation of accident chains. Furthermore, BN provides advantages for updating the status probability and for predictive and diagnostic calculation capabilities. Thence, BN approach for quantitative analysis is more accurate both structurally and probabilistically.

3. Methodology

In light of the review of the previous research, this study is designed to follow the process of FSA stipulated by IMO, including data collection, hazard identification to obtain significant basic events, and then BN are employed to analyze ro-ro space fire accident causal factors.

3.1. Data Collection

The data in this study is derived partly from those provided by the IMO FSA study on fire accidents on Ro-pax occurred between 2002 and 2012, (IMO, 2012) and partly from globally published relevant data sources concerning fire accidents on Ro-pax from 2012 to 2021. (IMO, 2016; IMO, 2018)[29][30] Further, to compensate for the potential insufficiency of both sources, the authors also include in the scope of the study some fire accidents that occurred on Chinese Ro-pax. They are collected from official reports of fire accidents, and some widely recognized journal articles recording fire accidents. A total of 62 cases of fire accidents on Ro-pax, ro-ro cargo ship and enclosed vehicle space are collected and then reviewed from a novel perspective to extract basic events and representative or typical accident causal chains.

Simply put, the fire accidents selected in this study are within the time period of 2002 to 2021 and are from three literature categories, namely, FSI 21-5 document, international public websites and accident investigation reports published by the competent authority of the government and authoritative journal articles in China. (Gao et al., 2007; China MSA, 2021)[31]

3.2. Fire hazards identification

The aim of identifying fire hazards is to discern typical basic events. Firstly, the previous key studies are reviewed to extract commonly recognized fire hazards, and then, the fire accidents collected (as stated in Section 3.1) are reexamined to identify specific fire hazards. Selected fire accidents in ro-ro spaces onboard ships are reexamined and leading factors for fire causes are highlighted as basis events, and the causal chains of fires are also established. Fire hazards in ro-ro spaces are categorized into three streams: failures of ship cargo, including human factors, technical failures, and failures of vehicles' lasing. Each stream accommodates a few fire hazards identified, which becomes the nodes of BN.

3.3. Estimation of occurrence of basic events

To determine the probability of basic events, the shipyears of 8716 from 2002 to 2018 presented in LASHFIRE report are quoted and then by averaging the figure, the authors make further estimation of another 3 years (from 2019-2021), thus the total shipyears of 9741 are obtained for the time period of 2002-2021. (RISE, 2021)

The probability for basic events (P_i)were calculated using Eq. (1). (Arslan et al., 2018; Uğurlu, 2011)[32][33].

$$P_i = \frac{\sum_{j=1}^{n} f_j(i)}{\mathrm{Y}}$$

$$f_j(i) = \begin{cases} 1/X_j & BE\ No.i\ occurred \\ 0 & BE\ No.i\ not\ occurred \end{cases} \tag{1}$$

where i is the number of basic event of FT, $i = 1, 2, 3 \ldots \ldots n$, X_j is the total number of basic events for the j accident, $j = 1, 2, 3 \ldots\ldots n$, Y is the shipyears, Y=9741.

Then, to calculate the probability of occurrence of intermediate events leading to the TE, Eqs. (2)-(4) are used. (Mohammadi et al., 2021)[34]

$$P_{or} = 1 - \prod_{i=1}^{n} (1 - P_i) \tag{2}$$

$$P_{and} = \prod_{i=1}^{n} P_i \tag{3}$$

$$P(TE) = 1 - \prod_{j=1}^{k} \left(1 - P\left(MCS_j\right)\right) \tag{4}$$

where P_i denotes the probability of the basic event i, $P\left(MCS_j\right)$ presents the probability of the minimum cut set j, and $P(TE)$ is the probability of TE.

3.4. Construction of BN

The authors of this paper have reexamined 62 fire accidents in ro-ro spaces on board Ro-pax between 2002 and 2021. Those fire accidents are documented in a few authentic data-like sources (see Section 3.1). Through reexamining those accidents, typical causality chains are identified and common causes of vehicle fires are listed to be used as skeletons of the BN. Further, the occurrences of the basic events in those accidents are accumulated to estimate the frequency of occurrences of basic event per shipyear. The BN is built with four branches, namely vehicle fuel tank leakage, manual failure, technical failure and cargo failure. Each branch is rooted respectively with basic events identified. The proposed BN has also been consulted with duly experienced experts from the Chinese domestic ferry shipping sector. The Construction of BN is showed in Fig 1.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 June 2023 doi:10.20944/preprints202306.0638.v1

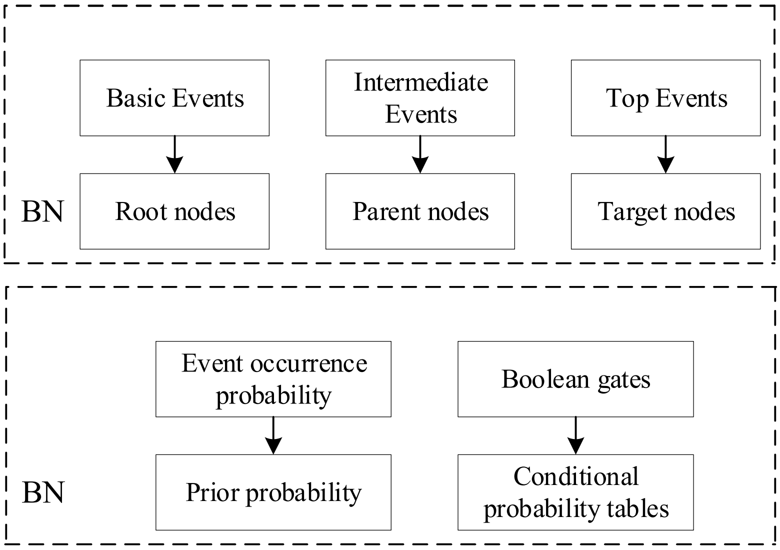

Figure 1. Construction of BN.

(sources: Khakzad et al., 2011; Sakar et al., 2021, modified by the authors)

The Ratio of Variation (ROV) and Birnbaum Importance Measure (BIM) are developed in BN to identify critical events, which is calculated by the Eqs. (5) and (6). (Mohammadi et al., 2021)

$$ROV(X_i) = \frac{P_o(X_i) - P_r(X_i)}{P_r(X_i)} \quad (5)$$

where, X_i, $P_o(X_i)$, and $P_r(X_i)$ are the number, the posterior probability, and the prior probability of the basic events respectively.

$$BIM(X_i) = P(T=1|X_i=1) - P(T=1|X_i=0) \quad (6)$$

where, X_i is the number of the basic events, and T is the TE.

3.5. Flowchart of the study

The flowchart of study is presented in Fig.2.

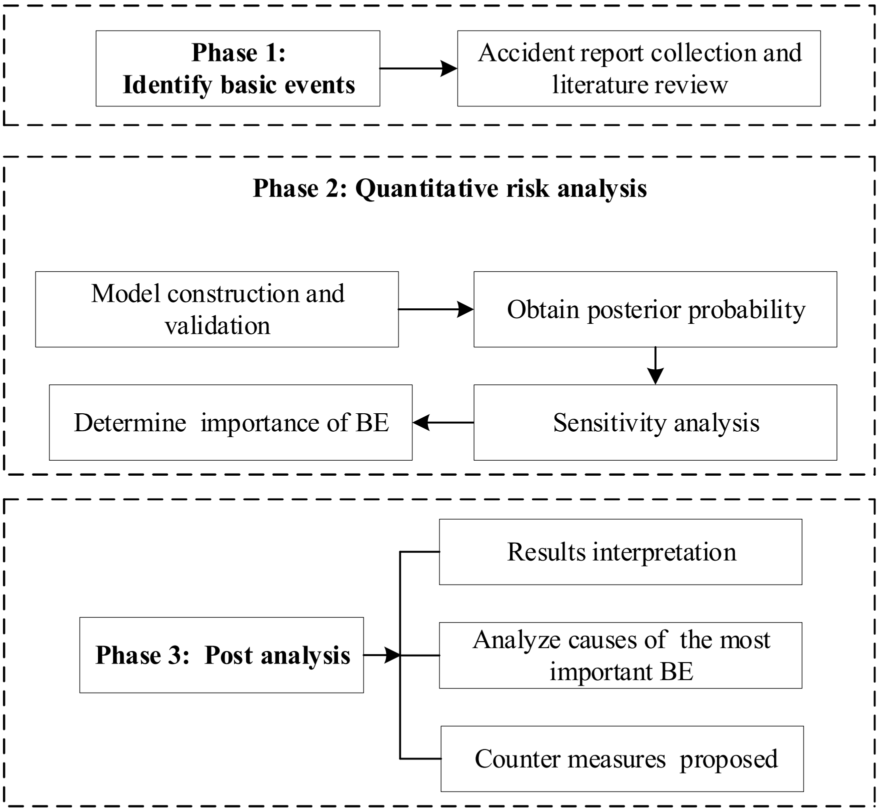

Figure 2. Roadmap of Study.

4. Case study

Following the designed methodology, the authors conduct a series of analyses of Ro-pax fire accidents, including BN analysis, BE probability reliability comparison, and the most significant event selection.

4.1. BN analysis of fires on Ro-pax

In this study, 17 basic events are extracted from the analysis of 62 cases of fire accidents and are listed under the three categories listed in Section 3.2 of this paper. The probabilities of Basic Events and The terms of Intermediate Events see Tables 1 and 2, respectively.

Table 1. Probabilities of Basic Events.

No.	Basic events	Expected values (BEs)	Probability (BE)
X1	insecure lashing/cargo shift	7	7.19E-04
X2	rough seas in heavy weather	7	7.19 E-04
X3	electrical boxes short circuit	1	1.03 E-04
X4	refrigeration socket transformer malfunction	1	1.03 E-04
X5	vehicle engine fire (fuel system fault)	4.33	4.45 E-04
X6	vehicle electric fire (electrical equipment defect or short circuit)	15.83	1.63 E-03
X7	used car electrical fire	6.33	6.5 E-04
X8	reefer units electrical fire (electrical appliances defects or short circuit	8.5	8.73 E-04
X9	lithium - ion battery - electric vehicles fire	0.33	3.42 E-05
X10	discarding non-extinguished cigarette butts	1	1.03 E-04
X11	combustible goods leaving behind	0.5	5.13 E-05
X12	staying overnight in cabs	0.5	5.13 E-05

X13	operating against rules or wrongly	0.83	8.55 E-05
X14	fire source in vehicle cabs	0.5	5.13 E-05
X15	cargo spontaneous combustion	8.17	8.38 E-04
X16	cargo burning (nature unknown)	2.67	2.74 E-04
X17	dangerous goods burning (undeclared or mis declared cargo)	0.83	8.55 E-05

Table 2. Terms of Intermediate Events.

No.	**Intermediate events**
M1	vehicle fuel tank damage
M2	technical failure
M3	cargo failure
M4	ship power supply equipment
M5	vehicle fires
M6	unsafe behavior of vehicle drivers
M7	cargo fires

A BN model is shown in Fig.4. This model is created using the GENIE software to define 24 connections representing the relationship between 25 nodes and then mapping algorithm to quantify the relationship among the variables. In addition, Two options of Yes" or "No" were assigned to each node in the network structure, where a "Yes" status represents the occurrence of the event, whereas a "No" status refers to a non-occurrence condition.

The prior probability of root nodes is the probability of occurrence of basic events. Besides, Logic gates and expert opinions are used in creating conditional probability tables (CPT(s)) which shows conditional probabilities for parent nodes in BN. Table 3 and Table 4 show the CPTs of the target node(fire) before and after expert judgement input. Three experts are invited to provide their judgement on corrections of probability of intermediate nodes. They are all bachelor degree holders, and also hold master or officer (of management level) competency certificates, and have served on Ro-pax exceeding 20 years. To avoid the possible bias or uncertainties brought about by the subjective judgment of the experts, the triangular fuzzy number is introduced for processing. (Bao et al., 2020; Kaptan, M., 2022).[35] [36]

Table 3. CPT of the target nodes.

	Node	**States**							
Fire	**M1**	**Yes**				No			
	M2	**Yes**		**No**		Yes		No	
	M3	Yes	No	Yes	No	Yes	No	Yes	No
	Yes	1	1	1	1	1	1	1	0
	No	0	0	0	0	0	0	0	1

Table 4. Corrected CPT of the target node (fire).

	Node	**States**							
Fire	**M1**	**Yes**				No			
	M2	**Yes**		**No**		Yes		No	
	M3	Yes	No	Yes	No	Yes	No	Yes	No
	Yes	0.98	0.95	0.95	0.95	0.95	0.9	0.95	0
	No	0.02	0.05	0.05	0.05	0.05	0.1	0.05	1

4.1.1. Model validation

Two fire accidents (See Table 5) are selected as new evidence to certify the applicability of the proposed BN model.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 June 2023 doi:10.20944/preprints202306.0638.v1

Table 5. Synopsis of the accidents.

Ship name	Basic events
Yinghua	1). Spontaneous combustion of cargo 2). Cargo burning (nature unknown） 3). Dangerous goods burning (Undeclared or mis-declared cargo)
Pearl of Scandinavia	1). Misconduct of vehicle drivers 2). Vehicle electric fire (electrical equipment defect or short circuit)

Changing the statuses of basic events involved in two accidents (See Table 5) to "Yes" in the BN model, the probability of fire increased to 0.9311 and 0.8946, respectively. The occurrence of fire in both cases is higher than 0.9, which shows the validity of the BN model used in this paper. The status changes by the basic events from Yinghua fire accident is demonstrated in Fig.3.

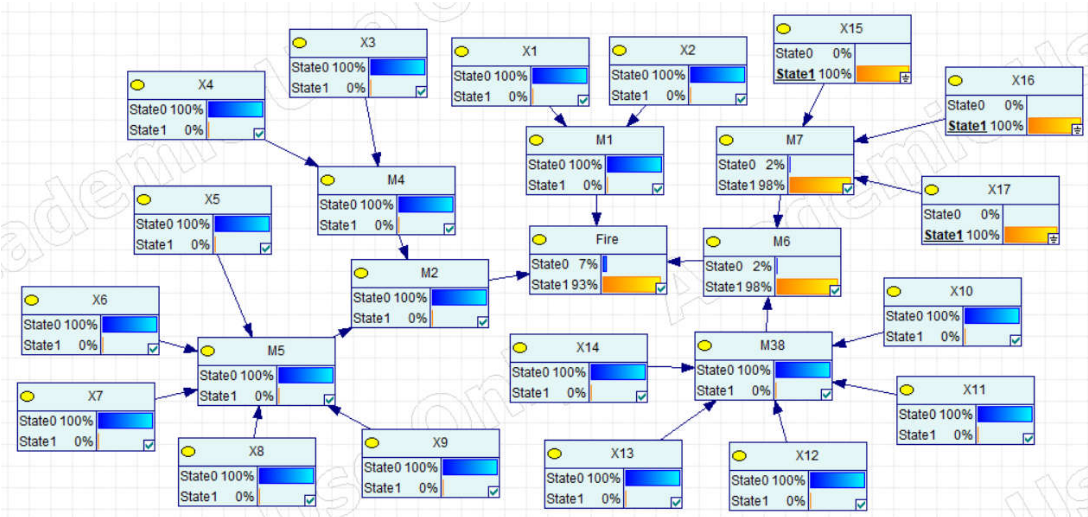

Figure 3. Changes in the BN model with new evidence of Yinghua fire accident.

4.1.2. Sensitivity analysis

The validated model is then applied to the reasoning process. By setting the target node (fire) as evidence, the posterior probabilities are obtained, as is shown in Table 6. Then, the maximum possible causal chain for the accident occurrence is determined, as is shown in Fig.4.

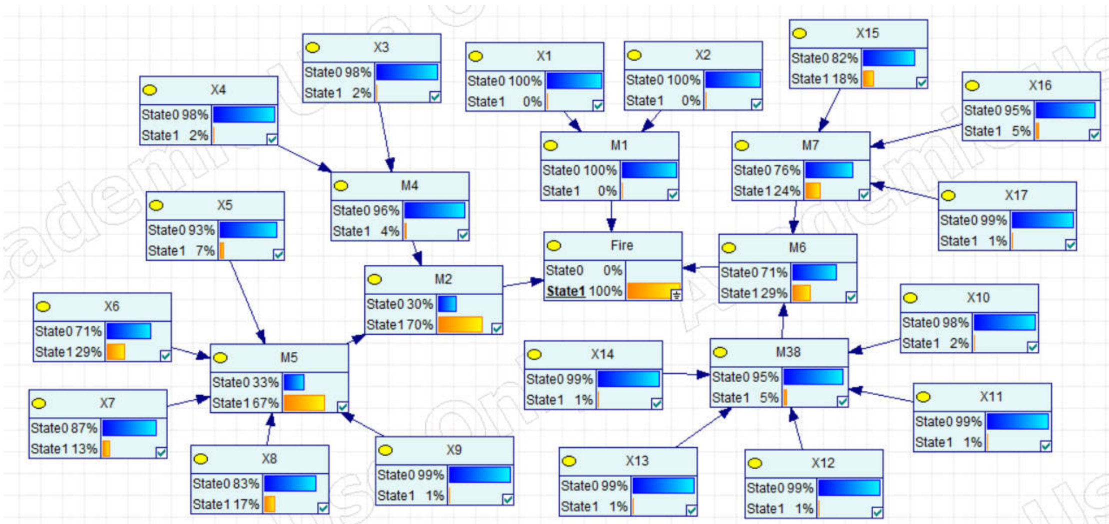

Figure 4. The maximum possible causal chain for occurrence of accidents.

Figure 4. indicates that the route of X6—M5—M2—Fire has the highest possibility. Therefore, these events are specially focused. However, the highest possible chain, representing only the

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 June 2023 doi:10.20944/preprints202306.0638.v1

formation mechanism of the majority of accidents, cannot exclude other chains. Hence other highly possible factors such as X5、X7、X8、X15、X16 are also considered when proposing risk control actions .

In this study, Eqs. (5) and (6) are used to analyze the most critical basic event. The results are presented in Table 6.

Table 6. Results of ranking the importance of the basic events.

BE	Posterior probability (BN)	ROV		BIM	
		Result	Rank	Result	Rank
X1	0.0024	2.338	16	0.010	16
X2	0.0024	2.338	16	0.010	16
X3	0.0194	187.350	6	0.806	6
X4	0.0194	187.350	6	0.806	6
X5	0.0745	166.416	10	0.717	10
X6	0.2897	176.730	8	0.762	8
X7	0.1264	193.462	4	0.833	5
X8	0.1697	193.387	5	0.834	4
X9	0.0068	199.000	2	0.860	2
X10	0.0159	153.369	14	0.663	11
X11	0.0079	153.902	12	0.662	13
X12	0.0090	175.471	9	0.757	9
X13	0.0132	154.294	11	0.662	12
X14	0.0079	153.902	12	0.662	13
X15	0.1757	208.666	1	0.899	1
X16	0.0544	197.540	3	0.851	3
X17	0.0094	109.588	15	0.473	15

Fig.4 demonstrates the most important basic events leading to TE. It can be observed that such factors as X3, X4, X5, X6, X7, X8, X9, X12, X15 and X16 are the top factors and further investigation is needed.

4.3. BE probability reliability comparison

Findings of frequency as per shipyear for fires from previous studies are summarized in Table 7 (for conventional vehicles) and Table 8 (for HEV, BEV or Refrigeration unit/RU vehicles) respectively. Correcting the CPTs brings down the fire probability to 4.31E-03, and this value is in the same order but two times higher than that of the DNV-GL study (DNV-GL, 2016), which is 2.0E-03 for 2005-2016. But it is comparable to that of FIRESAFE II study (EMSA, 2018), which is 5.28E-03 for 2002-2016, (See Table 7). In addition, the probability of BEV is 0.342E-04, and this value is in the same order but three times lower than that of the BMVBS study (BMVBS, 2013), which is 1.06E-04 for 1994-2004. And the probability of RU is 8.73E-04, and this value is in the same order but two times higher than that of the BMVBS study (BMVBS, 2013), which is 4.94E-04 for 1994-2004. (See Table 8).

The differences mentioned above can be attributed to the use of different approaches in respective analyses. Firstly, while the previous studies all concentrated on the occurrence of top events (fires) which leads to the frequency of fires as per shipyear, this study focuses on the root causes, that is, the occurrence of basic events are utilized to justify the probability of the top events; simply put, the differences are the result of different statistic approach. Secondly, more fire accidents are included in the present study, including the 10 fire accidents happened in Chinese coastal waters from 2002 to 2021, documented in Chinese version journals and the recent accidents worldwide from 2017 up to 2021. As claimed by Allianz in 2022, fires have become a consistent loss driver for car carriers over the past decade, and in many cases, fires involving vehicle cargoes have resulted in the total loss of cargo and the vessel. (Allianz, 2022)[37]Those accident inputs can contribute to the higher probability of fire in this study than that in the previous ones.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 June 2023 doi:10.20944/preprints202306.0638.v1

Table 7. Summary of studies addressing Ro-pax fires.

Description of casualty	Study	Data	Ship category	Frequency (per shipyear)	Time Period analyzed
Fire or explosion in ro-ro space	SAFEDOR (IMO, 2008)	Lloyds Maritime Information Unit (LMIU)	Ro-pax above 1,000 grt	0.99E-03	1994-2004
Ship fire in ro-ro space	FIRESAFE II (EMSA, 2018)	EMSA data	Ro-pax	5.28E-03	2002-2016
Ship fire in ro-ro space	DNV GL (DNV GL, 2016)	International databases, class records, EMSA marine casualty reports, incident reports, interviews with owners	Ro-pax above 4,000 grt	2.0E-03	2005-2016

(Source: RISE, 2020, modified by the authors).

Table 8. Fires caused by HEV, BEV, or RU vehicles.

(not connected/connected to the ship's power distribution).

Vehicle type	Scenarios	Number of fires (per year)	Frequency (Per shipyear)
HEV/ BEV	not connected	0.3	1.06E-4
RU	connected	1.4	4.94E-4

(Source: BMVBS, 2013, modified by the authors).

4.4. Selection of the most important basic events

In this study, the criteria of critical importance, which measure the importance level of respective basic events by their sensitivity and probability, are used to determine the importance level of respective basic events. We adopt the method used in the literature (Vesely et al., 1981)[38] and compute the value of individual basic events importance, as is shown in Table 6.

Table 6 (Section 4.2) indicates that X15 (Cargo spontaneous combustion) is the most important causal factor of fire accidents in Ro-pax enclosed space, followed by X9 (lithium - ion battery - electric vehicles fire), X16 (cargo burning with reasons unknown), X8 (reefer units electrical fire (electrical appliances defects or short circuit)) and X7 (used car electrical fire).

They are followed by X3 (electrical box short circuit) and X4 (refrigeration socket transformer malfunction) in the sixth and seventh place. And what follows sequentially are X6 (vehicle electric fire (electrical equipment defect or short circuit)), X12 (staying overnight in cabs) and X5 (vehicle engine fire (fuel system fault)). Additionally, BN model is constructed and verified using GENIE software. To determine the significance order of basic events, both ROV and BIM methods are run and the results are approximately consistent. As is shown in Table 6, the first 5 groups of basic events of high possibility are (X15), (X7, X8, X9, X16), (X3, X4), (X6, X12), (X5).

5. Findings and discussion

The results of the first 10 important basic events obtained by the BN model, the most important basic events are X5, X6, X7 (those related to vehicle fires), X3, X4, X8 (those related to reefer unit fires), and X15, X16 (those related to cargo fires). In this section, all these basic events will be discussed in depth.

5.1. Vehicles electrical fires

This study reveals that vehicle-fire-related basic events X5, X6, X7 (prior probabilities being 4.45E-04, 1.63E-03, 6.5E-04 per shipyear, respectively) are among the first ten (posterior probabilities being 0.07, 0.29, 0.13) of the BN ranking, which indicates that the sources of vehicle electrical fires deserve further investigation.

Electrical faults originating in ships' cargo (vehicles carried onboard) is the most common cause of fires in ro-ro spaces. (RISE, 2020) According to an IMO study on causes of fire accidents in ro-ro spaces during the period of 1994 to 2011, electrical fires in vehicles constitute a significant portion. The review of Ro-pax fires in FIRESAFE I (EMSA, 2016) shows that approximately 60 % of the fires were caused by electrical faults. Vehicles, especially those in poor condition and thereby more prone to electrical faults and leaks, are also a common source of ro-ro space fires. (RISE, 2020) The symptoms of a poor-conditioned vehicles include aging electrical lines, heavy oil stains in the engine compartment, and fuel leaking, which may cause short circuits, sparking and even engine compartment fire. And short circuits of the vehicle storage batteries can also cause engine compartment fire.

One effective way to prevent battery short circuit is to disconnect the positive and negative electrodes of the vehicle battery and secure the connecting threads, which can effectively stop the threads from connecting and sparking when the ship vibrates and rolls heavily. Another proper practice is to assign persons to inspect, before vehicles boarding, the vehicles' electrical system condition. In a recent investigation report, U.S. National Transportation Safety Board (NTSB) recommends car carriers to establish battery securement procedures and a means to ensure that the procedures are followed through adequate oversight of vehicle loading and battery securement. Additionally, the items to be inspected can include identifying any faults in the electrical system that could result in short circuit or other unintended electrical source of ignition. (NTSB, 2021) A Chinese chief mate with 15 years of seagoing service on Ro-pax states in a semi-constructed survey that storage battery short circuit is the major cause of fires, and the five fire accidents he experienced are all caused by it. He further proposes that the effective action is to disconnect storage battery power supply and remove the positive and negative electric threads.

5.2. Reefer vehicle fires

The present study discovers that reefer vehicle related fires (X8) is the fourth in BN ranking (posterior possibility being 0.1697), and thus further analysis needs to be made. A study disclosed that the majority of sources of fires started from reefer units, and a significant number of the incidents occurred as a result of electrical fires, particularly relating to refrigerated trailers, though in some cases, fires originated from the ships' own equipment (IMO, 2012). The root causes are the defects of cables connecting the refrigeration unit with the power supply and sometimes the connection itself. (RISE, 2020) In addition, over one third of the fires that occurred in ro-ro space originated in ship's cargo, are caused by refrigeration units. (EMSA, 2016)

While refrigerated units typically constitute merely a rather limited proportion of the cargo carried onboard, it is, statistically, the most hazardous type of cargo in terms of both hazard probability and severity. (RISE, 2020) Ten participants of the semi-structured survey (four captains and six chief mates) presented their opinions on the causes of reefer vehicle fires, which can be summarized as over-aged engines on reefer vehicles, aging electrical lines, oil leakage from reefer vehicles, all-time powered cabs, overheated lines due to long-time cooling operations, and automatic initiation of cooling triggered by temperature rise of the refrigerated cabin during the voyage. This agrees with the RISE statement that electrical faults in refrigeration units are particularly dangerous. (RISE, 2020) Therefore, it can be justified that improving the safety of refrigerated units transportation will be beneficial to risk reduction in ro-ro spaces; ship operators need to focus on the more vulnerable and fire-prone refrigeration units connected to the ship's power supply.

The risk control actions proposed by some officers of management level are inspecting reefer vehicles conditions beforehand to ban those with leaking oil symptoms from boarding the ship, stowing the reefer vehicles properly isolated from other cargo, appointing special attendance to them, conducting regular patrol, standing by fire-fighting appliances during the voyage and avoiding long-time refrigerating operation to avoid fires caused by power line overheating.

5.3. Vehicle-carried cargo fires

This study finds that basic events related to vehicle-carried cargo fires (X15, X16) are among the first three in BN ranking (posterior probability being 0.1757 and 0.0544 respectively). And this indicates that vehicle-carried cargo fires are worth further investigation.

According to a Chinese captain of ro-ro passengers ship in a semi-structured survey, three key causes of ignition for ro-ro spaces are cargo on vehicles burning, poor vehicle conditions, vehicle cargo shifting caused by rough seas, and improper cargo stowage. Factors relevant to vehicle-carried cargo fires are undeclared or mis-declared cargo and the cargo with nature unknown to the crew. One captain states that the enormous diversities of the goods make it difficult for crew to have sufficient knowledge of the nature of the goods.

Special attention should also be paid to the flammable or explosive gases emitted from the burning vehicle-carried cargo (e.g. chemical reaction of burning silicon mud with sea water can emit hydrogen which may accumulate in the enclosed space) because they may cause successive explosions. Take two cases of spontaneous combustion of the truck-carried cargo onboard a Chinese Ro-pax for example. At 2206 LT on April 19th, 2021, spontaneous combustion happened on a truck carrying silica mud on board Vessel Zhonghua Fuqiang. At 2231 LT, the master commanded to seal Deck 3 and started the fixed CO_2 fire extinguishing system (CO_2 released). After the vessel returned to port and berthed, the master evacuated all passengers and most crew from the ship. At 0031 LT on April 20th, the shore-based emergency fire-fighting department took over the fire-fighting, and at 1141 LT, they initiated opening the sealed space, and experienced two consecutive explosions. It is possible that at the initial stage of the fire-fighting, when the ship was at sea, the space was filled with large amount of flammable gas and hydrogen produced by reaction of high-temperature silica mud and hose water, and when the space was reopened, the influx of the fresh air mixed with the flammable gases like the hydrogen at the stern door led to the first explosion. And then, with the stern door opened wider and the first explosion causing negative pressure inside the space, more fresh air flew into the space. The flammable gases accumulated between two elevator wells caught another explosion when mixed with the incoming fresh air.

The lesson learned from the above-mentioned cases can be boiled down to the following: firstly, a timely and proper response to the fire can ensure that the ship may return to port to evacuate people from the ship, thus avoiding personal casualty. Secondly, refilling the sealed space with more CO_2 from the shore can be an effective way to suffocate the fire and ease the burning[39]. Finally, one of the effective measures to avoid the re-occurrence of similar accidents is that competent authorities inform the front-line operational staff by circulating the reports concerning causes of cargo burning and precautionary measures to take.

5.4. Potential causal factors of fire for LIB vehicle

This study discovers that basic event related to lithium-ion battery (LIB) vehicle fires (X9) ranks second in BN ranking (posterior probability is 0.0068). A car-maker industry study report reveals that since 2015, the average annual sale growth of global new energy vehicles is about 54%. Especially in 2021, this increase was recorded at 6.75 million, nearly twice that in 2020. In terms of pure electric vehicles, the global sales have reached 4.793 million, doubling the sales in 2020. (Zhan, Y.& Ji, Z., 2022)[40] In China, this growth was about 157%. In 2021, the volume of sales of new energy vehicles in China accounted for 50% of the global market, with the sales reaching 3.52 million, about 2.6 times that in 2020. (Zhan, Y.& Ji, Z., 2022) It is reasonable to anticipate great growth in demand for transporting new energy vehicles by sea. Meanwhile, it is especially critical for operators to plan their

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 June 2023 doi:10.20944/preprints202306.0638.v1

activities carefully concerning vehicle positioning and fire detecting and fighting in storage spaces. (McGregor et al., 2021) Therefore, the root causes of LIB vehicle fires are investigated further.

Generally, the primary cause of BEV/HEV fires is believed to be thermal runaway of LIB. Fires are more liable to occur due to self-ignition (or spontaneous/auto-ignition) in loaded vehicles sustained abuse such as improper charging. Once the onboard batteries catch fire, it is difficult to suppress it, and in particular, when a LIB catches fire， it is almost inextinguishable, because when the toxic compounds, composed of volatile organic compounds, hydrogen gas, carbon dioxide, carbon monoxide, soot, particulates containing oxides of nickel, aluminums, lithium, copper, cobalt, and hydrogen fluoride, accumulate in the enclosed space, the presence of an igniting source such as a spark or flame, electrical arcs will trigger the explosion, or the compounds may be self-ignited in a poor cooling condition. (Sun et al., 2020)[41]

DNV-GL identifies that “shift of cargo represents a risk” is particularly pertinent to the carriage of electric vehicles. According to the Journal of The Electrochemical Society, one condition leading to LIB thermal runaway is mechanical abuse /lashings failure, which means Electric Vehicle (EV) cargo shifting during the voyage due to lashing failure may lead to a thermal runaway and the ensuing fire. (Rich, 2022)[42] Therefore, giving EV cargo additional lashing to avoid cargo shifting in the seaway is a critical action to reduce EV vehicle fires.

Another hazard identified by vessel operators and electric vehicle experts is the risk related to electric vehicles charging without proper authorization. (MCA, 2021)[43] One academic study even highlight charging EV onboard may induce the risk of EV fires. (Wu, 2021) Hence, prohibiting charging EV vehicles to avoid thermal runaway, thus bringing down fire risks is also crucial. Additionally, the carriage of damaged electric vehicles can also pose greater fire risks. Therefore, a competent person should thoroughly inspect all electric vehicles before their being transported onboard. A suitably qualified person should be assigned to disconnect the battery pack if vehicles are towed or carried by a car transporter. (MCA, 2021)

In a nutshell, the following actions as is proposed by a chief mate with over 20 years sea going service experience on Ro-pax, can be taken to reduce the possibility of EV fire: firstly, EV cargo should be stowed individually under the attendance of personnel during the voyage as per company regulations, fire-fighting appliances on standby; secondly, there should be sufficient fire passageway to allow proper ventilation; thirdly, extra lashing should be placed on EV cargo to prevent the vehicle from shifting and colliding when lashings break; finally, bumping and colliding should be avoided when EV embarking or disembarking the ship to avoid physical damage to batteries, and movable fittings in the cargo space should be properly secured to prevent the batteries from being pierced or impacted.

5.5. Vehicle fires originating from human factors

Unsafe behaviors of vehicle drivers (human factor) are also a causal factor of fire. In the present study, five types of drivers’ hazardous behaviors (basic events) are identified, among which the comparatively important ones are discarding non-extinguished cigarette butts (X10), staying overnight in cabs (X12), and operating against rules or wrongly (X13). In BN ranking, X12 ranks ninth with a posterior probability of 0.009. One recent fire accident further indicates that drivers staying overnight in cabs can pose a high fire risk. (The Maritime Executive, 2022)[44] It is worth noting that electric quilts used in cabs in winter can be a hazard if the power is not completely cut off.

Therefore, the risk control actions for this type of hazard can include the following: observe the company safety supervision regulations strictly to prevent cab drivers and passengers from entering the vehicle space during the voyage; prohibit drivers from staying overnight in cabs, passengers from carrying flammable or explosive goods and people from discarding undistinguished cigarette butts.

6. Conclusions

In this study, 62 fire accidents in enclosed spaces on ro-pax selected from credential sources are reexamined to identify major fire hazards and establish typical causal chains. And the probabilities of basic events are determined as per ship year. Based on these efforts, the top event's probability is figured out, and the critical importance of basic events is prioritized. Those basic events X5(vehicle engine fire (fuel system fault)), X6(vehicle electric fire (electrical equipment defect or short circuit)), X7(used car electrical fire), X8(reefer units electrical fire (electrical appliances defects or short circuit)), X15(cargo spontaneous combustion) are prioritized by BN and are targeted for specific analysis in order to disclose the root causes of such events. A semi-constructed survey involving Chinese senior officers onboard Ro-pax is conducted to sort their opinions on potential hazards of fires and feasible solutions to reduce the fire hazards on board. In alignment with the findings of the study, some countermeasures are proposed, including disconnecting storage battery power supply and securing the positive and negative electric threads, avoiding automatic initiation of cooling triggered by temperature rising of refrigerated cabin during voyages, prohibiting recharging onboard, placing extra lashing on EV cargo and prohibiting drivers from staying overnight in cabs.

However, in this study, we are unable to construct individual branches of BN for LIB vehicle fires, used car electric fires, and reefer vehicle fires, since it has been impossible to determine the probability of occurrence for three fire events in case of setting them as immediate nodes. Hence, it is expected to investigate probability of occurrence for root nodes of three fire events individually, aiming at constructing complete BN of fire events onboard ro-ro ship by exploring available sources of datasets to determine probability of occurrence. In addition, to measure risk level of casualty on ro-ro passenger ships, PLL (Potential for Loss of Life) is to be calculated, hence the accumulated probability of fire in enclosed spaces needs to be determined, which is the input (initial frequency) of event tree analysis.

References

---

[1] International Maritime Organization (IMO). (2022). Safety of ro-ro ferries. Accessed on 30TH March, 2022, https://www.imo.org/en/OurWork/Safety/Pages/RO-ROFerries.aspx

[2] Kirk McGregor, Paul R. Nichols, Frank Anderson. (2021). A master's guide to: Fire safety on ferries. Accessed on May first, 2022, https://www.standard-club.com/fileadmin/uploads/standardclub/Photos/Thumbnails/SC-MG-Fire-safety-on-ferries-20210527_Final.pdf.

[3] IMO. (2016). MSC 96/INF.3. Formal safety assessment, including general cargo ship safety. Electric mobility on ro-ro and ro-pax ships report of the formal safety assessment (FSA) study.

[4] International Union of Marine Insurance (IUMI). (2017). Fires on ro-ro passenger vehicle decks. Accessed on 30TH March 2022, https://iumi.com/images/IUMI_Position_Paper_-_Fires_on_RoRo_Passenger_ferries_-_7_February_2017.pdf

[5] China Maritime Safety Administration (China MSA). (2021). Investigation report of fire accidents onboard vessel Zhonghua Fuqiang in Weihai port of China.

 doi:10.20944/preprints202306.0638.v1

---

[6] The Maritime Executive, (2022). Salvage tugs arrive to fight fire aboard burning ro/ro Felicity Ace. Accessed on 30TH March 2022, https://maritime-executive.com/article/salvage-tugs-arrive-to-fight-fire-aboard-burning-ro-ro-felicity-ace

[7] DNV GL. (2016). A report on fires on ro-ro decks. Accessed on 30TH March 2022, https://maritimesafetyinnovationlab.org/wp-content/uploads/2022/02/DNV-GL-Fires-on-Ro-Ro-Decks-2016.pdf

[8] IMO. (2019). MSC 101/17 - Formal safety assessment: FIRESAFE I and II studies – FSA on fires on ro-ro decks of passenger ships, submitted by Austria et al.

[9] Research Institutes of Sweden (RISE). (2021). LASH FIRE. Deliverable D04.2 ro-ro space fire database and statistical analysis report.

[10] IMO. (2008). MSC.255(84) - adoption of the code of the international standards and recommended practices for a safety investigation into a marine casualty or marine incident (casualty investigation code).

[11] China Ministry of Transportation (China MOT). (2021). Guidelines for statistics of water traffic accidents, as amended by No.23 order of China Ministry of Transportation.

[12] IMO. (2007). MSC83/INF.2 - Consolidated text of the guidelines for formal safety assessment (FSA) for use in the IMO rule making process (MSC/Circ. 1023 – MEPC/Circ. 392).

[13] DNV. (1996). "Safety assessment of passenger roro vessels", Main Report (Document Number: REP-T09-003), Joint North West European Project, 28.10.1996.

[14] IMO. (2008). MSC 85/INF.3 - FSA: RoPax ships details of the formal safety assessment, submitted by Denmark.

[15] IMO. (2016). MSC 96/INF.3 - Formal safety assessment, including general cargo ship safety: Electric mobility on ro-ro and ro-pax ships report of the formal safety assessment (FSA) study, submitted by Germany.

[16] IMO. (2012). FSI 21/5. Casualty statistics and investigation: Report of the correspondence group on casualty analysis, submitted by Canada.

[17] RISE. (2020). LASH FIRE: Review of accident causes and hazard identification report.

[18] Endrina, Nieves & Rasero Balon, Juan & Konovessis, Dimitrios. (2018). Risk analysis for ropax vessels: A case of study for the Strait of Gibraltar. Ocean Engineering. 151. 141-151. 10.1016/j.oceaneng.2018.01.038.

[19] Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., & Dadashzadeh, M. (2018). Review and analysis of fire and explosion accidents in maritime transportation. Ocean Engineering, 158, 350-366.

[20] United States Coast Guard (USCG). (2020). Recognizing fire hazards & proper cargo stowage on ro-ro vessels. Accessed on 30[TH] March 2022, https://maritimesafetyinnovationlab.org/wp-content/uploads/2021/12/USCG-MSA-06-20-RECOGNIZING-FIRE-HAZARDS-PROPER-CARGO-STOWAGE-ON-RO-RO-VESSELS.pdf

[21] Papanikolaou, A., Bitha, K., & Eliopolou, E. (2015). Statistical analysis of ship accidents that occurred in the period 1990-2012 and assessment of safety level of ship types. In G. G. Soares, & T. Santos, Maritime Technology and Engineering (pp. 227-233).

[22] Antao, P., & Soares, C. G. (2006). Fault-tree models of accident scenarios of ropax vessels. International Journal of Automation and Computing 2, 3(002), 107-116.

[23] Daqing Wang, Peng Zhang, Liqiong Chen, Fuzzy fault tree analysis for fire and explosion of crude oil tanks, Journal of Loss Prevention in the Process Industries,Volume 26, Issue 6,2013,Pages 1390-1398,ISSN 0950-4230, https://doi.org/10.1016/j.jlp.2013.08.022.

[24] Ali, T. Ö. Z., BÜBER, M., KÖSEOĞLU, B., & ŞAKAR, C. Analysis of collision accidents in maritime transportation by FTA method. Turkish Journal of Maritime and Marine Sciences, 1-16.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 June 2023 doi:10.20944/preprints202306.0638.v1

[25] Hasan Ugurlu, Ismail Cicek, Analysis and assessment of ship collision accidents using fault tree and multiple correspondence analysis, Ocean Engineering, Volume 245,2022,110514, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2021.110514.

[26] Ibrahim, H., Rao, P., 2019. Fire risk analysis in FLNG processing facility using Bayesian network. JESTEC 14 (3), 1497–1519.

[27] Koski, T. J. T., & Noble, J. (2012). A review of Bayesian networks and structure learning. Mathematica Applicanda, 40(1). https://doi.org/10.14708/MA.V40I1.278

[28] Cenk Sakar, Ali C. Toz, Muge Buber, Burak Koseoglu, Risk analysis of grounding accidents by mapping a fault tree into a Bayesian network, Applied Ocean Research, Volume 113,2021,102764, ISSN 0141-1187, https://doi.org/10.1016/j.apor.2021.102764.

[29] IMO. (2018). SSE 6/6/1 - Review SOLAS Chapter II-2 and associated codes to minimize the incidence and consequences of fires on ro-ro spaces and special category spaces of new and existing ro-ro passenger ships: Review of relevant recent accident investigation reports from the EU, submitted by Austria et al.

[30] IMO. (2016). MSC 96/INF.3 - Formal safety assessment, including general cargo ship safety: Electric mobility on ro-ro and Ro-pax ships Report of the formal safety assessment (FSA) study, submitted by Germany.

[31] Gao Sifu, Liu Dagang and Chen Lei. (2007). Analysis of Bohai ro/ro passenger ship fire accidents and management countermeasures. NAVIGATION OF CHINA (01), 55-59.

[32] Arslan, Ö., Zorba, Y., Svetak, J. 2018. Fault tree analysis of tanker accidents during loading and unloading operations at the tanker terminals. Journal of ETA maritime science, 6(1).

[33] Uğurlu, Ö. (2011). Petrol tankerlerinde meydana gelen deniz kazalarının risk analizi. (Doktora Tezi). Trabzon: Karadeniz Teknik Üniversitesi Fen Bilimleri Enstitüsü.

[34] Mohammadi, H., Fazli, Z., Kaleh, H., Azimi, H. R., Moradi Hanifi, S., & Shafiee, N. (2021). Risk analysis and reliability assessment of overhead cranes using fault tree analysis integrated with markov chain and fuzzy Bayesian networks. Mathematical Problems in Engineering.

[35] Bao, J., Bian, Z., Yu, Z., Phanphichit, T., Wang, G., & Zhou, Y. (2021). A Hybrid Approach to Risk Analysis for Critical Failures of Machinery Spaces on Unmanned Ships by Fuzzy AHP. In International Conference on Neural Computing for Advanced Applications (pp. 273-287). Springer, Singapore.

[36] Kaptan, M. (2022). Analysis of accidents during vehicle stowage on RO-RO vessels by using Fuzzy Bayesian networks. Ocean Engineering, 260, 111997.

[37] Allianz Global Corporate & Specialty (Allianz). (2022). Safety and shipping review 2022: An annual review of trends and developments in shipping losses and safety. Accessible at: https://www.agcs.allianz.com/news-and-insights/news/safety-shipping-review-2022.html

[38] Vesely, W. E., Goldberg, F. F., Roberts, N. H., & Haasl, D. F. (1981). Fault tree handbook. Nuclear Regulatory Commission Washington DC.

[39] IMO. (2021). SSE 8/INF.7 - Information on the results of an experiment on shore-based supplement of fire-extinguishing agent for ro-ro passenger ships, submitted by China.

[40] Zhan, Y.& Ji, Z. (2022). New energy vecicle industry analysis report of 2022. https://max.book118.com/html/2022/0420/7015036136004113.shtm

[41] Sun, Peiyi, Bisschop, Roeland, Niu, Huichang and Huang, Xinyan. (2020). A review of battery fires in electric vehicles. Fire Technology. 1-50. 10.1007/s10694-019-00944-3.

[42] Rich Madden. (2022). Electric vehicles and maritime transportation - Fire hazards identified (gcaptain.com), accessed on 23rd feb.2022, https://gcaptain.com/electric-vehicles-and-maritime-transportation-fire-hazards-identified/

 doi:10.20944/preprints202306.0638.v1

[43] U.K. Maritime & Coastguard Agency (MCA). (2021). MGN 653 (M) - Electric vehicles onboard passenger ro-ro ferries. Accessed on 23rd feb.2022, https://www.britishmarine.co.uk/News/2021/October/Consultation-on-guidance-for-the-carriage-and-charging-of-Electric-Vehicles-on-Ro-Ro-ferries

[44] The Maritime Executive. (2022). Fire reignites aboard ro/ro Euroferry Olympia as search continues. Accessed on 23rd feb.2022, https://www.maritime-executive.com/article/fire-reignites-aboard-ro-ro-euroferry-olympia-as-search-continues