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A HYBRID DEMATEL–ISM AND BAYESIAN NETWORK APPROACH FOR THE RISK ASSESSMENT OF NIGHTTIME LIQUEFIED NATURAL GAS CARRIER OPERATIONS

Summary. Safe navigation of liquefied natural gas (LNG) carriers is critical for maintaining efficiency and mitigating catastrophic accident risks in modern maritime logistics, with heightened risks and operational challenges under nighttime conditions, which constitute the focus of this study. This study develops a hybrid methodological framework by integrating decision-making trial and evaluation laboratory–interpretive structural modeling (DEMATEL–ISM) with Bayesian networks to systematically identify, structure, and quantify risk factors associated with nighttime LNG carrier operations. First, key risk elements, spanning human, vessel, environmental, and managerial dimensions, are extracted via expert surveys and accident case reviews. DEMATEL–ISM is then employed to establish a multi-level hierarchical model that elucidates the direct and indirect causal relationships among these factors. The findings indicate that diminished ambient illumination and restricted visibility are deep-level triggers that propagate through psychological stress, visual performance degradation, and operational errors, ultimately increasing accident likelihood. Subsequently, a Bayesian network model is constructed by mapping the hierarchical structure onto probabilistic dependencies, allowing forward and backward inferences that pinpoint critical risk propagation pathways. The quantitative results reveal that risk chains predominantly originate from environmental disturbances and escalate when coupled with insufficient training, suboptimal management procedures, and human fatigue. These insights highlight the necessity for targeted interventions, including enhanced port lighting designs to minimize glare, scientific scheduling to counteract circadian disruptions, and strengthened on-site supervision through refined Vessel Traffic Services management and emergency response protocols. Overall, this integrated analytical framework provides both theoretical underpinnings and practical guidelines for improving nighttime LNG carrier safety, offering a valuable reference for researchers and stakeholders in maritime transportation risk management.

1. INTRODUCTION

Natural gas, as a high-quality, efficient, and environmentally friendly low-carbon energy source, plays a pivotal role in advancing the energy production and consumption revolution. Accelerating its development and utilization while ensuring coordinated and stable growth constitutes a crucial pathway for establishing a modern energy system characterized by cleanliness, carbon reduction, safety, and

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efficiency. According to China's Energy Production and Consumption Revolution Strategy, the national energy consumption is projected to be capped at 6 billion tons of standard coal equivalent by 2030, with natural gas accounting for approximately 15% of primary energy consumption [1].

Forecasts indicate that China's liquefied natural gas (LNG) imports will maintain an average annual growth rate of around 10% from 2020 to 2030 and will predominantly be transported via maritime shipping [2]. However, the inherent physicochemical properties of LNG—namely, its cryogenic temperature, high volatility, and flammability—pose significant safety challenges. Any leakage during transportation or storage may trigger cascading hazards, including asphyxiation, cryogenic burns, rapid phase transition phenomena, and potential fire scenarios such as flash fires, jet fires, pool fires, or even vapor cloud explosions when encountering ignition sources [3-5]. Not only do these accident scenarios jeopardize vessel integrity and crew safety, but they also threaten port infrastructure and surrounding ecosystems with catastrophic consequences.

In maritime safety research and operational practices concerning LNG carriers, current efforts predominantly focus on navigation during port inbound/outbound, berthing, and cargo handling operations. This prioritization stems from the catastrophic potential of operational errors during these critical operational aspects [6,7]. Risks are substantially amplified during nighttime navigation operations due to constrained visibility, complex waterway environments, high traffic density, and crew fatigue [8].

Nighttime navigation of LNG carriers involves maritime activities conducted between sunset and sunrise the following day, including port approaches, docking maneuvers, and departure procedures. Standard protocols designed to mitigate accident risks during these operations involve establishing safety zones within port approaches and implementing traffic control measures. While these measures enhance safety to some extent, they also impose significant constraints on port operational efficiency and economic performance. This conflict has positioned the optimization of navigational management and operational procedures for LNG carriers—particularly in achieving equilibrium between safety imperatives and operational efficiency—as a persistent research focus among the academic community and in industrial practice.

In current engineering practices, many countries and regions have adopted conditionally permitted nighttime LNG operations through risk mitigation measures such as dual-pilot deployment, operational time restrictions, and phased implementation. However, China's delayed adoption of nighttime LNG operations has resulted in insufficient risk management protocols for critical stages, including nocturnal port approaches and berthing operations. This deficiency primarily stems from inadequate risk awareness, leading to early-warning inaccuracies, consequently exposing nighttime LNG operations to elevated safety risks. As a result, China currently conducts minimal nighttime LNG shipping operations and has yet to establish comprehensive risk control frameworks or corresponding regulatory standards.

Concurrently, existing research predominantly focuses on daytime LNG navigation safety, with limited scholarly attention devoted to nocturnal operations. Current methodologies can be categorized into qualitative and quantitative approaches. Qualitative methods, such as hazard identification [9] and Hazard and Operability Study (HAZOP) [10], employ node criticality analysis to identify risk components and assess risk levels. However, these approaches exhibit excessive reliance on expert subjectivity. Recent advancements have introduced quantitative analytical frameworks in LNG navigation safety assessments. Liu et al. [11] developed a fuzzy analytic hierarchy process model to quantify navigation risks using the entrance channel of Zhangjiagang Port's Dongsha terminal as a case study. Liu et al. [12] established a risk evaluation index system comprising 12 indicators across four dimensions (human, vessel, environment, and management) through Delphi and expert judgment methods, employing entropy-weighted fuzzy modeling to mitigate subjective bias in weight determination. Han et al. [13] implemented Bayesian network modeling to analyze risk factors from four perspectives (human, machinery, environment, and management), constructing conditional probability tables through historical data and expert evaluations to identify critical risk elements. Beyond conventional maritime risk-assessment methods, recent human-centered design studies have proposed light-guided navigation support tools to mitigate nocturnal perceptual degradation and improve situational awareness [14]. Related work has further examined maritime head-up display concepts as a potential way to support information acquisition while managing visual clutter in

demanding navigation conditions [15]. Evidence from other mission-critical transport domains, such as aviation, also shows that harsh light and glare can measurably degrade visual performance during safety-critical stages, underscoring illumination and glare control as upstream contributors to operational risk [16].

Therefore, this study establishes an innovative analytical framework for LNG carrier nighttime operations through causal association modeling, elucidating the interaction mechanisms among complex risk factors and their evolutionary patterns during nocturnal navigation. The remainder of this paper is organized as follows: Section 2 presents the DEMATEL–ISM-based causal association analysis and hierarchical modeling. Section 3 develops the Bayesian network model and performs probabilistic inference. Section 4 discusses the findings, limitations, and a data-driven validation roadmap. Finally, Section 5 concludes the paper.

2. DEMATEL-ISM BASED ANALYSIS OF CAUSAL ASSOCIATION EFFECTS

Fig. 1 presents the research roadmap. The proposed framework comprises three phases. First, a hybrid DEMATEL–ISM approach is used to investigate interdependencies among latent risk factors and establish a multi-level hierarchical structure that reveals direct and cascading risk propagation pathways. Second, Bayesian network modeling quantifies critical risk elements during accident progression through probabilistic inference. Finally, the synthesized findings inform targeted mitigation strategies in both operational management and technological interventions.

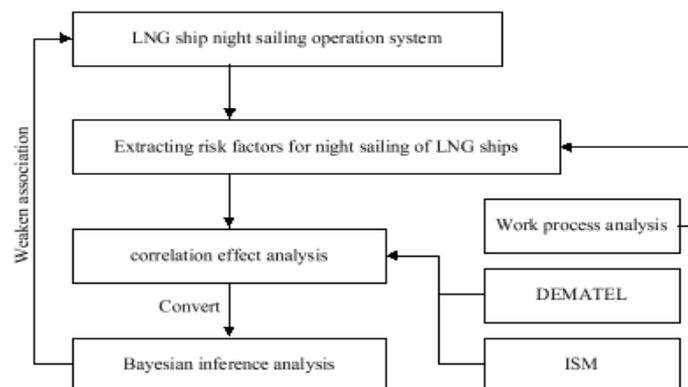


Fig. 1. Research technology roadmap

2.1. Risk factor identification

Given the scarcity of nighttime LNG carrier operations and corresponding accident records, this study adopts an expert survey methodology to extract risk factors. Through a systematic analysis of nocturnal operational characteristics and daylight accident reports, we establish a risk factor framework specific to nighttime LNG navigation. The operational workflow for LNG carriers during nighttime navigation is illustrated in Fig. 2.

Under the SAFEDOR initiative, DNV researchers compiled 182 LNG carrier incidents starting from 1959 (the inaugural LNG cargo transportation), as reported up to 2007 [17]. The dataset comprises 24 non-operational incidents (including shipyard construction, maintenance, sea trials, and towing operations) and 158 navigation-related accidents. The categorical distribution and proportional representation of these historical incidents are detailed in Table 1. To contextualize the evolving safety landscape, more recent casualty statistics can be consulted in continuously updated official databases such as the IMO GISIS Maritime Casualties and Incidents (MCI) module and the EMSA EMCIP annual overviews [21, 22].

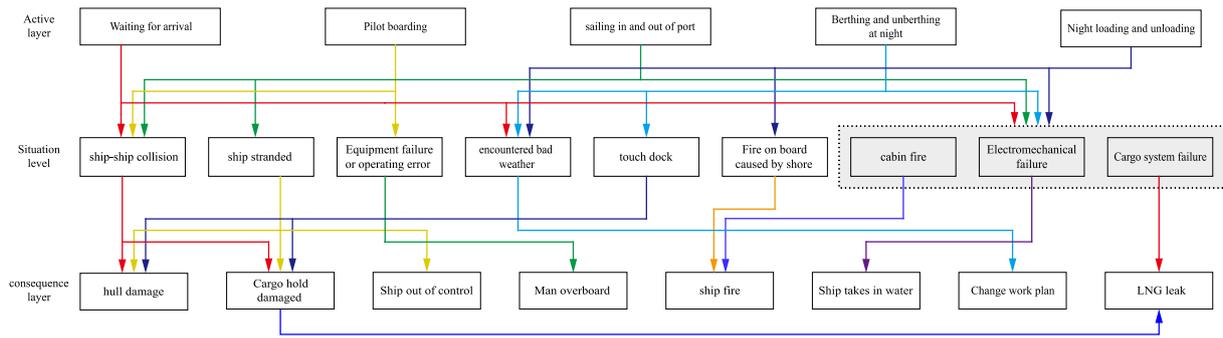


Fig. 2. Night sailing operation process of LNG ships

Table 1
LNG carrier historical accident types and distribution (SAFEDOR compilation, 1959-2007)

Accident type	Statistical data
Collision	19
Stranded	8
Contact damage	10
Fire and explosion	10
mechanical failure	55
Wind damage and wave damage	9
Loading and unloading accident	22
Storage system failure	27

Compared to daylight operations, LNG carrier nighttime navigation presents two critical risk amplifiers First, drastically reduced ambient illumination coupled with intense background lighting in port areas induces visual fatigue among operators (Fig. 3), elevates psychological stress, and degrades environmental perception accuracy, thereby compromising decision-making efficacy. Second, human circadian rhythm troughs during nighttime hours substantially increase fatigue-induced operational errors.



Fig. 3. Background glare phenomenon of a domestic LNG receiving station terminal

Through field research, the ship activities of LNG ships during night sailing can be summarized as five processes: LNG ships waiting to enter the port, pilots boarding the ship at night, LNG ships entering and leaving the port under tugboat escort conditions at night, and LNG ships berthing and leaving the port under tugboat-assisted operation conditions at night. Risk scenarios include a collision between an LNG vessel and another vessel, the stranding of an LNG vessel, the failure or misoperation of boarding equipment, bad weather, an LNG vessel touching a terminal, a fire on an LNG vessel (caused by either a shore-based fire or a fire on the vessel), mechanical and electrical equipment failure, and cargo system failure. The consequences of the above scenarios include hull damage, cargo damage, ship flooding, people overboard, ship fires, ship control, changes of operation plan, and LNG leakage. Referring to

the research on the causes of complex system accidents during the night sailing operation of LNG ships, the causes of accidents are divided into four categories: human factors, ship and equipment factors, management factors, and environmental factors. Keywords and word frequency are extracted according to the characteristics of the night sailing operation of LNG ships and standard requirements, combined with daytime navigation safety accidents. According to the classification of LNG accident causes, the risk feature words are summarized and screened, and the risk causes of LNG ship night sailing are finally obtained, as shown in Table 2. The marked risk factors are set $A = \{a_i | i = 1, 2, \dots, n\}$.

Table 2

Risk factors of LNG ship navigation operations

Accident Cause	Risk factors
Human factors	Competency a_1
	Navigation experience a_2
	Training situation a_3
	Visual performance a_4
	Psychological stress a_5
	Staffing a_6
	Mental state a_7
	Work level a_8
Ship and equipment factors	Equipment configuration a_9
	Main engine and steering gear condition a_{10}
	Ship maneuverability a_{11}
	Equipment aging a_{12}
Environmental factor	Weather conditions a_{13}
	Visibility conditions a_{14}
	Ambient illumination a_{15}
	Channel conditions a_{16}
	Traffic density a_{17}
	Navigation aids a_{18}
Management factors	Operating procedures and rules a_{19}
	Emergency mechanism a_{20}
	On-site supervision a_{21}
	VTS management a_{22}

2.2. Interdependency analysis

The nocturnal operation of LNG carriers involves complex interdependencies among risk factors. For instance, reduced ambient illumination degrades visual performance, thereby amplifying psychological stress and mental fatigue, which subsequently impairs operational decision-making. To deconstruct these causal chains, we implement an integrated DEMATEL–ISM methodology that systematically analyzes factor interactions and reconstructs them into a multi-tiered hierarchical model, thereby elucidating accident causation mechanisms.

On the basis of on-site investigation and preliminary hazard identification, an expert questionnaire was conducted to elicit pairwise influence strengths among the candidate risk factors for nighttime LNG carrier operations. A total of 67 questionnaires were distributed through professional channels spanning

ship operators, pilot/tug services, vessel traffic services and traffic management, and terminal safety management. From these questionnaires, 58 complete and consistent responses were retained for the subsequent DEMATEL–ISM scoring and Bayesian network probability elicitation. All respondents were professionally qualified in navigation or maritime traffic/terminal safety and were familiar with nighttime navigation and LNG terminal operations. The questionnaire elicited the pairwise direct influence between risk factors (i.e., whether factor a_i directly affects factor a_j). After summarizing the questionnaires, the mutual influence relationship between the risk factors was determined, and the direct influence matrix was constructed. The results are shown in Table 3.

Table 3

Direct effects relationship matrix

Factor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	1	1	0	3	2	1	3	0	0	0	0	0	0	0	0	0	0	1	2	2	1
2	3	0	1	2	3	2	2	3	0	0	0	0	0	0	0	0	0	0	1	2	2	1
3	3	3	0	2	3	2	2	3	0	0	0	0	0	0	0	0	0	0	1	1	2	2
4	3	2	2	0	3	1	3	3	0	0	0	0	0	0	0	0	0	0	1	2	3	2
5	3	2	2	1	0	1	3	3	0	0	0	0	0	0	0	0	0	0	0	1	2	2
6	1	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2
7	3	0	0	3	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	3	3
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	2	1	3	3	1	1	3	0	0	0	0	0	0	0	0	0	0	0	1	1	2
10	2	1	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	2	2	1	0	3	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	1	0	1	2	1	2	2	1	3	3	0	0	0	0	0	0	0	0	0	0	0
13	2	1	1	2	2	2	2	2	0	1	2	1	0	3	2	2	2	0	0	1	1	0
14	2	1	1	3	3	2	2	1	0	0	0	0	0	0	1	1	2	1	0	1	2	0
15	3	2	2	3	3	1	3	2	0	0	0	0	0	2	0	2	2	1	0	2	2	0
16	2	2	2	2	3	1	1	1	0	1	2	1	1	0	0	0	1	0	0	1	0	0
17	1	2	1	1	2	1	2	2	0	0	2	1	1	0	0	2	0	0	1	1	0	1
18	2	1	1	1	1	0	1	1	0	0	0	0	0	0	0	1	1	0	1	1	0	0
19	2	2	3	0	2	3	2	2	2	2	1	1	1	0	0	0	0	0	0	0	1	0
20	2	2	1	0	1	2	0	1	0	1	0	0	1	0	0	0	0	0	1	0	1	0
21	1	1	0	0	2	2	1	1	0	1	0	0	0	0	0	0	0	0	1	0	0	1
22	1	1	0	0	2	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Score scale: 0 = no influence, 1 = low, 2 = moderate, 3 = high.

The direct influence matrix is normalized to obtain the normalized influence matrix C , and the comprehensive influence matrix T is obtained by Equation (1):

$$T = C(I - C)^{-1} \tag{1}$$

where I is the identity matrix (dimension $n \times n$). Based on the comprehensive influence matrix T , four DEMATEL indicators are calculated for each factor a_i . The influence degree represents the overall influence exerted by factor a_i on other factors, which is computed as the row sum of T and denoted as D_i .

$$D_i = \sum_{j=1}^n t_{ij}, (i = 1, 2, \dots, n) \tag{2}$$

The influenced degree represents the overall influence received by factor a_i from other factors, which is computed as the column sum of T and denoted as C_i .

$$C_i = \sum_{i=1}^n t_{ij}, (i = 1, 2, \dots, n) \tag{3}$$

The centrality of factor a_i is denoted as M_i .

$$M_i = D_i + C_i \tag{4}$$

The causality (cause degree) is denoted as R_i .

$$R_i = D_i - C_i \tag{5}$$

If the cause degree is greater than 0, it indicates that the factor has a greater degree of influence on other factors, which is called the cause factor; otherwise, it is called the result factor.

According to Equations (1)–(5), the influence degree, influence degree, centrality degree, and cause degree of each factor are calculated, as shown in Table 4.

Table 4

DEMATEL calculation results

Factor	Influence degree	Influenced degree	Centrality	Causality	Factor	Influence degree	Influenced degree	Centrality	Causality
a_1	1.067	2.86	3.927	-1.793	a_{12}	1.071	0.187	1.258	0.884
a_2	1.444	1.921	3.365	-0.477	a_{13}	2.142	0.225	2.367	1.917
a_3	1.591	1.401	2.992	0.190	a_{14}	1.694	0.196	1.890	1.498
a_4	1.645	1.663	3.308	-0.018	a_{15}	2.201	0.12	2.321	2.081
a_5	1.291	3.187	4.478	-1.896	a_{16}	1.536	0.316	1.852	1.220
a_6	0.713	1.872	2.585	-1.159	a_{17}	1.498	0.313	1.811	1.185
a_7	1.195	2.313	3.508	-1.118	a_{18}	0.898	0.077	0.975	0.821
a_8	0	2.977	2.977	-2.977	a_{19}	1.643	0.749	2.392	0.894
a_9	1.268	0.245	1.513	1.023	a_{20}	0.913	1.375	2.288	-0.462
a_{10}	0.523	0.495	1.018	0.028	a_{21}	0.717	1.958	2.675	-1.241
a_{11}	0.813	0.436	1.249	0.377	a_{22}	0.614	1.591	2.205	-0.977

The centrality and cause degree values of the risk factors were calculated from Table 4, and the cause-effect graph was drawn (Fig. 4).

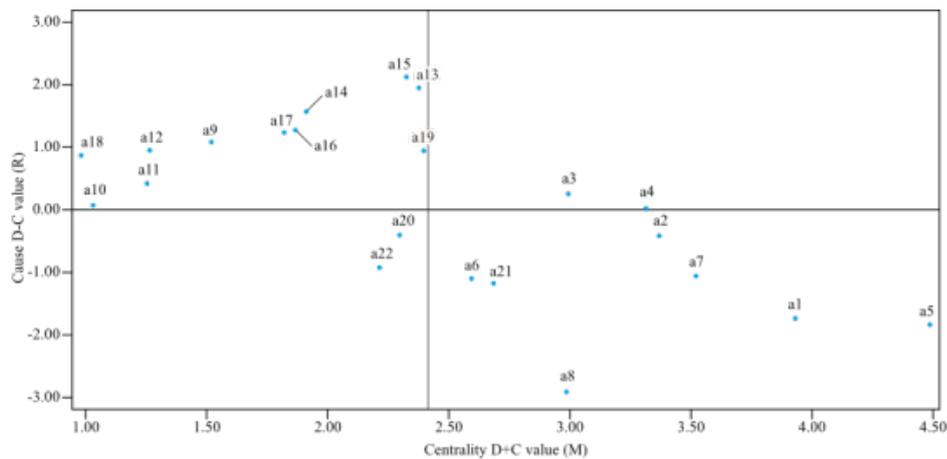


Fig. 4. Cause-effect plot based on DEMATEL

To derive the ISM adjacency (and reachability) matrix, we binarized the total influence matrix T using a threshold λ : $a_{ij} = 1$ if $t_{ij} \geq \lambda$, and $a_{ij} = 0$ otherwise. We selected λ by inspecting the node-degree attenuation curve (Fig. 5) and choosing the knee point where increases in λ yield diminishing reductions in the average node degree, thereby avoiding an overly dense graph (small λ) and the loss of dominant relations (large λ). A brief sensitivity check with $\lambda \in \{0.10, 0.12, 0.14, 0.16\}$ shows that

the key causal chain and layer structure remain stable within $\lambda = 0.12\text{--}0.16$. Accordingly, λ is set to 0.14 for the main analysis.

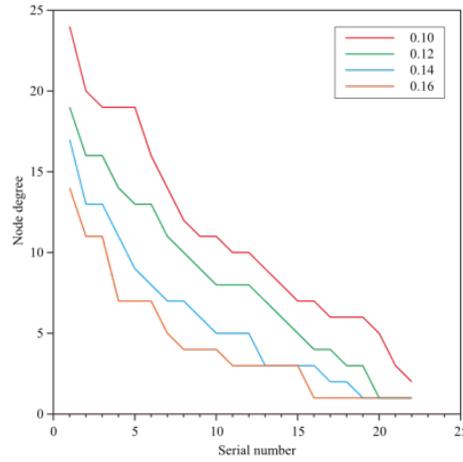


Fig. 5. Scatter plot of node degree attenuation of risk factors for the night sailing of LNG ships

When λ is 0.14, the node degree is moderate, and the reachable matrix F is obtained according to Equation (6):

$$f_{ij} = \begin{cases} 1 & e_{ij} \geq \lambda(i, j = 1, 2, \dots, n) \\ 0 & e_{ij} < \lambda(i, j = 1, 2, \dots, n) \end{cases} \quad (6)$$

Through the factors corresponding to the column with value 1 on row i of the reachability matrix F , the reachability set $R(x_i) = \{x_j | F_{ij} = 1\}$ is obtained, which represents the set of all factors that can be reached from the factor x_i . The antecedent set $S(x_j) = \{x_i | F_{ij} = 1\}$ is obtained based on the factors corresponding to the column with value 1 on the j th column of the reachability matrix F , which represents the set of all factors that can reach the factors. If $R(x_i)$ and $S(x_j)$ meet $R(x_i) \cap S(x_j) = R(x_i)$, then the corresponding reason of factor x_i can be found from $S(x_j)$, then the factor can be called a high-level factor. In turn, the row and column of the corresponding factor are deleted from the reachability matrix, and the highest-level factor is extracted from the remaining reachability matrix in a loop until all the rows and columns are deleted. Thus, the risk factors for daytime and nighttime navigation of LNG ships can be divided into four levels, as shown in Fig. 6.

According to Fig. 6, the greatest risk factors in the night sailing operation of LNG ships are environmental illumination conditions, weather conditions, visibility conditions, training conditions of night sailing operation, navigation aids, and traffic density. The training conditions of night sailing operation, weather conditions, visibility conditions, navigation aids, and traffic density are the inputs of the safety system. These factors affect the overall safety of LNG night navigation operation. Intermediate factors include operator competency, psychological stress, vessel handling performance, operational procedures and regulations, night sailing experience, staffing, mental state, visual performance, main engine and steering gear condition, equipment aging condition, equipment configuration, and channel conditions, which are affected by both the deepest risk factors and direct factors. Direct factors include emergency response mechanisms, operational levels, on-site supervision, and VTS management.

3. ANALYSIS OF ACCIDENT CAUSE MECHANISM BASED ON BAYESIAN NETWORK

Coupling among risk factors can alter the system risk state and propagate through the system, potentially culminating in an accident. Bayesian networks provide a natural formalism to represent such

causal dependencies and to perform probabilistic inference [19], [20]. Therefore, a Bayesian network is used to quantify the occurrence probability of risk factors during LNG ship night sailing and to analyze risk transmission paths, thereby revealing the accident causation mechanism.

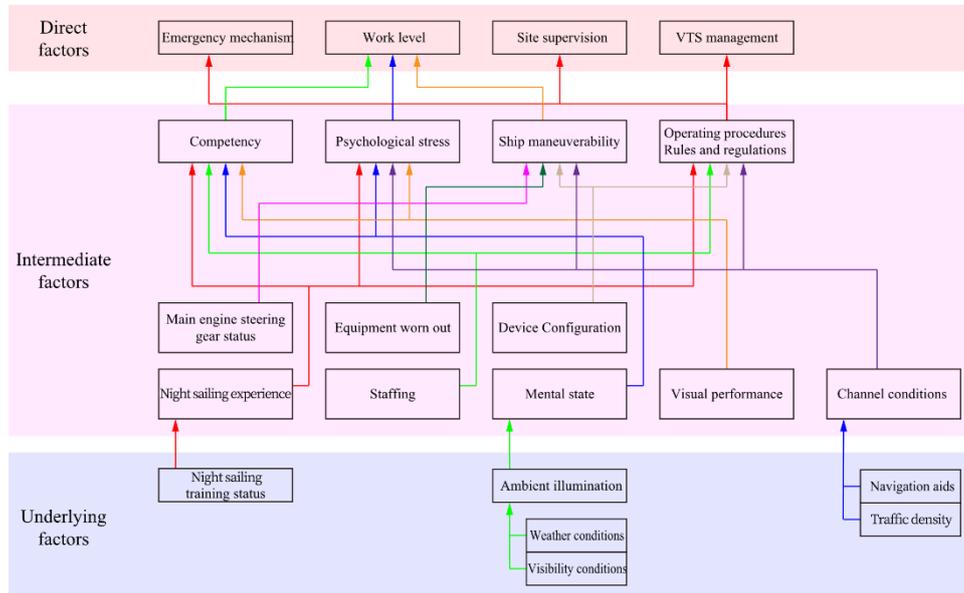


Fig. 6. Multi-level hierarchical ISM model

3.1. Methodology of the Bayesian Structure

Bayesian network is widely used in maritime risk assessment, including navigational risk estimation and accident cause/consequence analysis [20]. A prerequisite for Bayesian network analysis and reasoning is the construction of the Bayesian network topology to represent qualitative dependencies. Considering the complexity and interaction of the risk transmission links, the multi-level hierarchical ISM model (Fig. 7) is transformed into a Bayesian network topology in which each risk factor is mapped to a corresponding node.

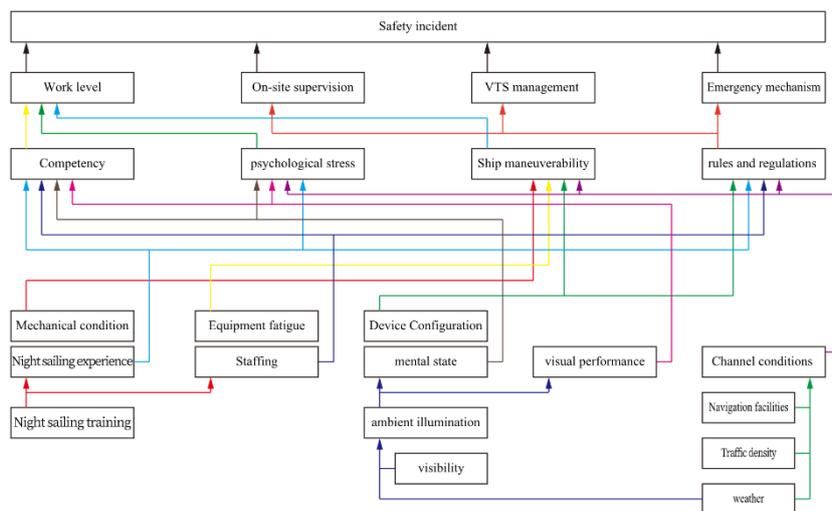


Fig. 7. Bayesian network inference structure

3.2. Determine the probability of risk occurrence

Considering the low frequency of LNG ships sailing at night, there are few accidents involving foreign LNG ships sailing at night, and it is difficult to obtain complete accident data. In future work, empirical sources such as AIS/VTS and radar tracks, ECDIS/voyage plans, bridge logbooks, VDR data, and official investigation reports can be integrated to estimate priors and conditional probability tables, which would reduce the current reliance on expert elicitation. Therefore, with the help of expert opinions, fuzzy evaluation was introduced as the occurrence prior probability of risk factors at the input end of the LNG ship sailing safety system. Expert opinions are expressed in the form of linguistic variables, denoted as "very high," "high," "average," "low," and "very low." The relation of each linguistic variable with respect to fuzzy numbers is shown in Table 5.

Table 5

Semantic values to the corresponding fuzzy numbers

Serial number	Semantic value	Fuzzy number
1	Very high	(0.8, 0.9, 1.0)
2	Higher	(0.6, 0.7, 0.8)
3	Generally	(0.4, 0.5, 0.6)
4	Lower	(0.2, 0.3, 0.4)
5	Very low	(0, 0.1, 0.2)

Using the expert panel described in Section 2.1, 58 valid responses provided linguistic assessments of prior and conditional probabilities for the Bayesian network nodes (Table 5). The linguistic terms were mapped to triangular fuzzy numbers and then defuzzified to obtain point estimates, which were used to parameterize the Bayesian network, as computed by Equation (7).

Equation (7) is used to mean the probability, and the mean area method is used to convert the fuzzy probability of the risk of LNG ships sailing at night and during the day into a precise probability.

$$P = \frac{a + 2b + c}{4} \quad (7)$$

In Equation (7), a , b , and c denote the lower bound, most likely value, and upper bound of the triangular fuzzy number, respectively.

3.3. Bayesian inference analysis

After the conditional probabilities are obtained, the posterior probabilities of each risk factor are determined by likelihood estimation inference, as shown in Figs. 8 and 9. Among them, the occurrence probability of each risk factor during daytime sailing of LNG ships is generally lower than that during night sailing, and only the probability of insufficient sailing training and sailing operation experience is relatively large. During the night sailing of LNG ships, due to the significant reduction of environmental illumination, the factors causing the greater probability of risk in the night sailing operation of LNG ships include poor visual performance, poor mental state, insufficient night sailing training of participants, insufficient night sailing experience, discomfort, increased psychological pressure, decreased operation level, and inadequate on-site visibility. Prevention and control strategies should focus on minimizing the occurrence of night sailing accidents of LNG ships.

The forward reasoning results in Fig. 8 show that the risk causes of the daytime general navigation operation safety system of LNG ships are relatively small and mainly involve personnel training and operation experience, starting from human causes, to management disorder coupling causes, and finally inducing general navigation safety accidents. Safety risk can be significantly reduced by strengthening the safety training of operators, improving their operation experience, strengthening the on-site supervision and management, and VTS management.

The forward reasoning results in Fig. 9 reveal that the risk factors in the safety system of LNG ship night-sailing operations generally follow the following pathway: environmental disturbance → coupling of management deficiencies and human factors → safety accident. By analyzing the posterior probability of each node, the root nodes with the most significant posterior probabilities can be identified as key links in risk transmission. Therefore, the critical path for LNG ship night navigation is obtained as follows: environmental illumination decline → visual performance deterioration → psychological pressure increase → operational performance decline, which ultimately leads to a safety accident. Accordingly, it is necessary to strengthen operator safety training, improve operational experience, and enhance on-site supervision and VTS management. More importantly, glare should be minimized while improving ambient illumination, and fatigue should be mitigated through structured watch rotation and adequate rest management.

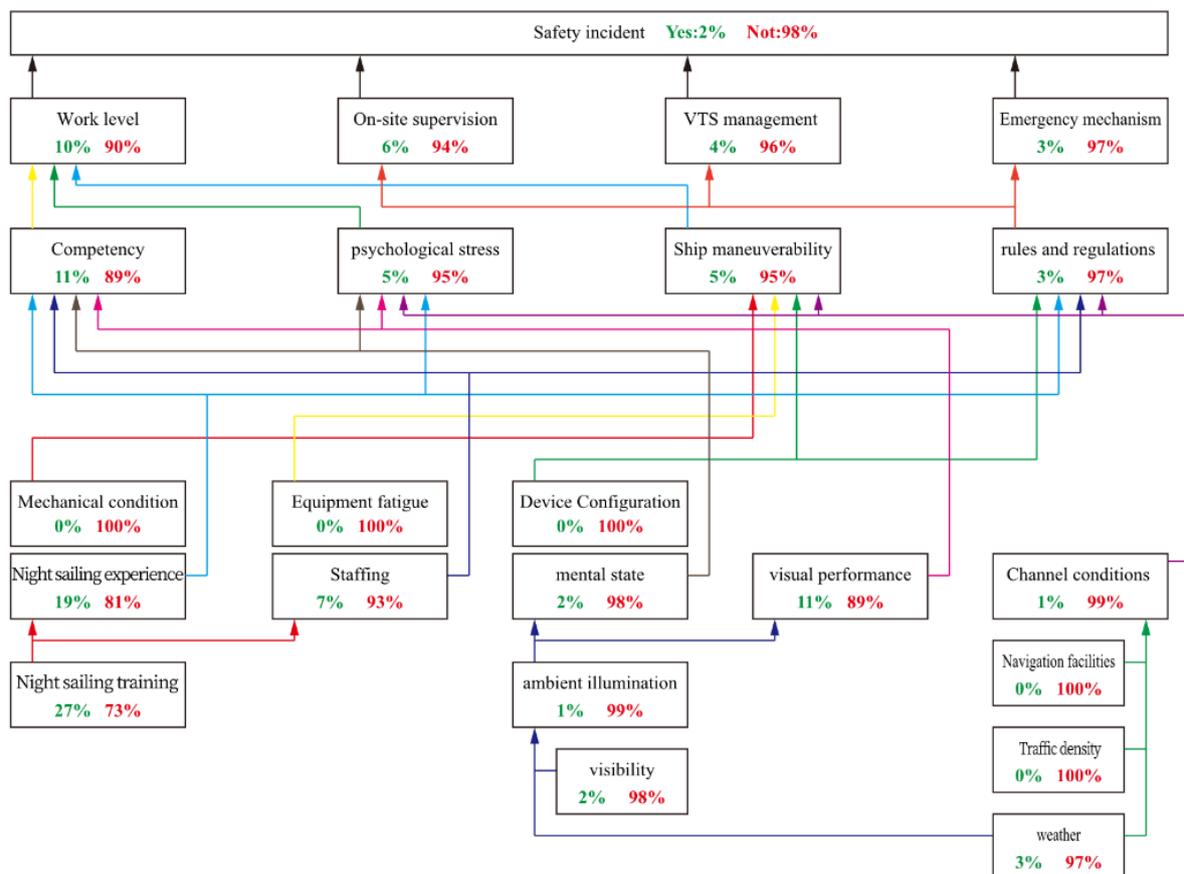


Fig. 8. Bayesian inference results of the risk probability for daytime navigation of LNG ships

4. DISCUSSION

The DEMATEL–ISM hierarchy and Bayesian inference jointly indicate that nighttime accident risk is dominated by an environmental–human–operation transmission chain. Insufficient ambient illumination and background glare can impair visual adaptation and target detection, which elevates workload and psychological stress and ultimately increases operational errors. Similar performance degradations under harsh light/glare have been reported in other mission-critical domains such as aviation, supporting the plausibility of treating glare control as a first-class safety variable in bridge operations and terminal lighting management [20].

From a control perspective, the identified root nodes suggest that the highest leverage is achieved by jointly improving the visual environment and decision support as follows. First terminal and channel lighting should be optimized to provide adequate illuminance while minimizing glare and contrast loss. Second, navigation aids and bridge information presentation should be enhanced to support nighttime situational awareness, consistent with recent design research on navigation support tools and maritime HUD concepts [21,22]. Third, night-operation training and shift rotation should be strengthened to mitigate fatigue, complemented by VTS coordination and standardized emergency procedures.

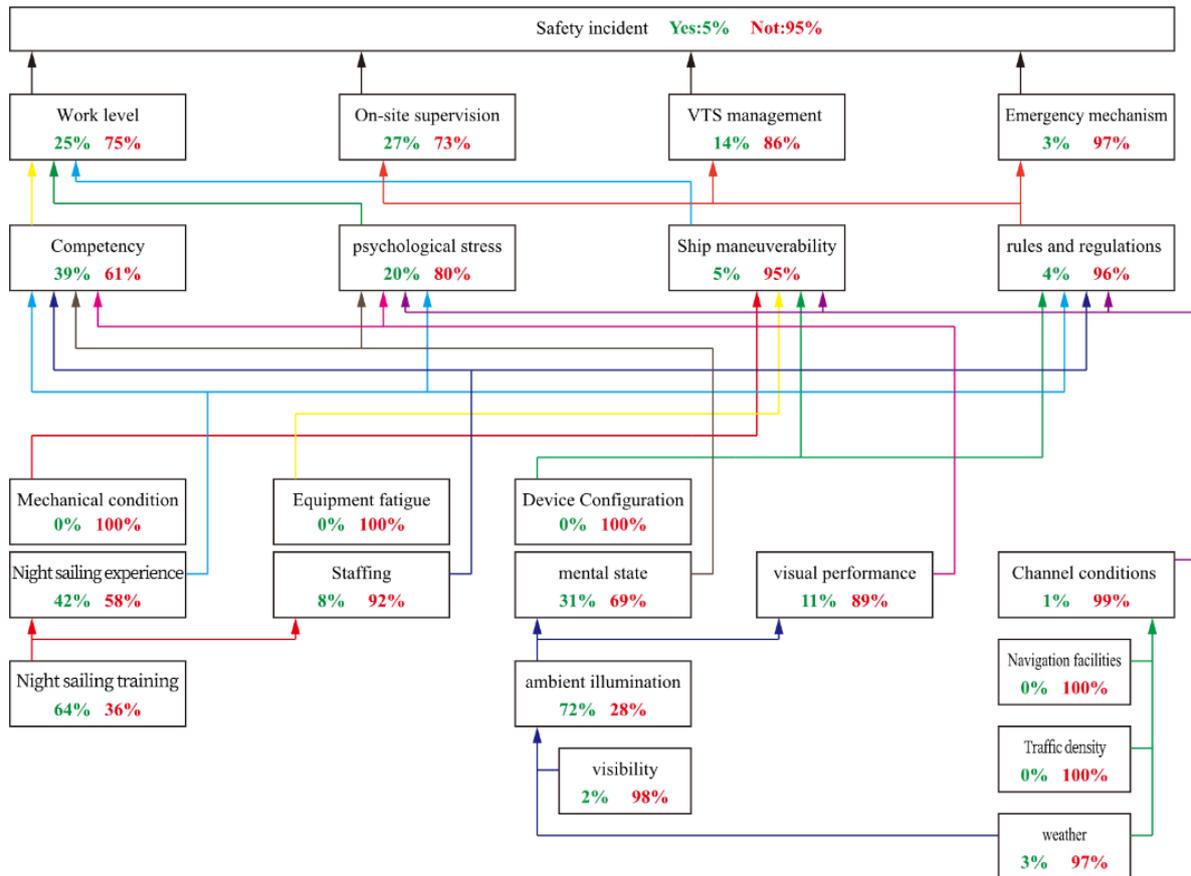


Fig. 9. Bayesian inference results for the risk probability for the night sailing of LNG ships

This study is limited by its reliance on expert elicitation (see the panel described in Section 2.1) for influence scoring and Bayesian priors due to the scarcity of nighttime accident records. Furthermore, the case context reflects current practice in Chinese ports. Nevertheless, the proposed DEMATEL–ISM.

Bayesian network workflow is transferable and can be validated and updated using routinely available operational evidence (AIS/VTS tracks, radar logs, VDR/bridge logs, pilot/tug records, meteorology/visibility and illuminance measurements, and near-miss reports) through Bayesian updating without increasing model complexity.

5. CONCLUSIONS AND FUTURE WORK

In this study, a hybrid DEMATEL–ISM and Bayesian network framework was developed to analyze coupled risk factors associated with nighttime LNG carrier operations. The DEMATEL–ISM results reveal a four-level structure in which environmental conditions and system support act as root inputs that propagate through human and procedural factors to direct management controls. Bayesian

inference further highlights the dominant risk chain of insufficient environmental lighting → degraded visual performance → increased psychological stress → operational errors. This chain indicates that improving the visual environment and managing fatigue/stress are key means of risk reduction. Future work will prioritize incorporating empirical evidence to refine parameterization, including AIS/VTS and VDR records, terminal lighting and glare measurements, and near-miss/incident datasets, enabling adaptive updates of conditional probabilities as new data become available.

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