

A novel integrated method for the risk assessment of ship to ship LNG bunkering operations

Bo Wang ¹, Hongbin Xie ^{2*}, Bixian Lyu ³, Zheng Chen ⁴, Deqing Yu ⁵, Yuhao Cao ⁶

Abstract: In recent years, Liquefied Natural Gas (LNG) has gradually become an alternative fuel for ships. For targeted safety management of ship to ship LNG bunkering, this study aimed to develop a new method to identify, quantify and rank the risk influential factors (RIFs) for fuel spills during the process of ship to ship LNG bunkering. Firstly, starting from the process of ship to ship LNG bunkering, the fuel leakage RIFs of ship to ship LNG bunkering are identified and summarized. Secondly, combining Failure Mode and Effect Analysis (FMEA), Bayesian Networks (BN) based on Fuzzy Belief Rule (FBRBN) and Evidential Reasoning (ER), a risk assessment model is proposed to quantify the risk level of the RIFs. Finally, through the case study of Zhoushan LNG bunkering station, the feasibility and practicability of the established risk evaluation index system and research methods are verified. The results of this study shows that "improper handling by personnel" is the most important RIFs affecting the safety of ship to ship LNG bunkering. Based on the results, targeted preventive measures are also proposed to enhance the safety of ship to ship LNG bunkering.

Key words: Maritime safety; LNG bunkering; Risk assessment; Evidential reasoning; Bayesian Network

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21 **Introduction**

22 Due to the advantages of high calorific value and clean combustion, LNG fuel has
23 gradually become an environmentally friendly alternative fuel for ships (Cao *et al.*,
24 2023b). With the tightening of the International Maritime Organization's low-sulphur
25 fuel standard and emission zone policy for ships, which has led to an increasing number
26 of LNG-powered ships gradually coming into operation (Gu, 2020). At present, the fuel
27 bunkering methods for LNG-powered ship mainly include five types: tanker, shore
28 station, bunkering ship, barge and floating equipment (Sharma *et al.*, 2022). Among
29 them, ship to ship LNG bunkering has obvious advantages in terms of mobility, quantity
30 and efficiency (Shi *et al.*, 2013). Thus, an increasing number of countries, ports and
31 companies are investing more and more in research and practices in this field year by
32 year (Chen, 2022).

33 LNG fuel also has the hazardous characteristics of low temperature, flammable,
34 explosive, and prone to evaporation (Tam, 2022). The most serious consequence of an
35 accident during bunkering operations would be the leakage of LNG fuel, which could
36 lead to fires and explosions. As ship to ship LNG bunkering operations mostly take
37 place in harbours and anchorages, an accident will cause incalculable damage to the
38 natural environment and human life (Ha *et al.*, 2022). Therefore, it is necessary to carry
39 out a comprehensive and systematic risk assessment of ship to ship LNG bunkering in
40 order to take corresponding measures in a targeted manner to ensure operational safety.

41 At its core, risk assessment is an efficient way of designing measures to prevent
42 accidents by measuring the potential influence of an incident on human life, property
43 and other factors through the lens of systems engineering (Wang *et al.*, 2023). Risk
44 assessment of ship to ship LNG bunkering research can help stakeholders understand
45 the RIFs leading to accidents. Furthermore, this study will provide scientific guidance
46 for the development of effective prevention and control measures. However, due to few
47 ship to ship LNG bunkering operations in practice, there is a lack of data to support the
48 risk assessment. At the same time, ship to ship LNG bunkering operation is carried out
49 in port waters, which is inevitably affected by the natural environment and navigational

50 environment. The compatibility of the operating ships and the types of the incoming
51 and outgoing ships are complicated and changeable. Above all, the uncertainty
52 characteristics of the risk assessment of ship to ship LNG bunkering fuel leakage is
53 particularly prominent. Therefore, it is important to choose an appropriate risk
54 assessment method to address these issues in this study.

55 In the field of risk assessment, FMEA is one of the prevalent approach in process
56 analysis because of its visibility and simplicity (Fan *et al.*, 2022; Fang *et al.*, 2023). In
57 addition, previous research has suggested additional techniques to improve the
58 effectiveness of risk assessment, such as ER, Analytic Hierarchy Process (AHP) and
59 BN. For example, Wang *et al.*, (2023) proposed a risk assessment model to quantify
60 and rank RIFs by combining FMEA, Belief rule based Bayesian Networks (BBN) and
61 ER in the process of Human Evacuation from Passenger Ships. Yu *et al.*, (2020)
62 formulated a semi-qualitative risk model that incorporates BN and ER methods to
63 assess the hazards related to vessel-turbine collisions. Asuquo *et al.*, (2021) utilised a
64 combination of ER and AHP algorithms to evaluate the functional uncertainties of a
65 specific equipment within a marine and offshore facility. Yu *et al.*, (2021) identified and
66 quantified RIFs by combining geometrical analyses of collisions between ship and
67 offshore installation with the BN method, which can be used to assess collision risks
68 involving different navigational environments. Yu *et al.*, (2021b) considers static risk
69 profiles, geographical-dependant risk factors and other local characteristics that affect
70 navigational safety, and combines BN and ER methods to achieve an assessment of the
71 overall risk to coastal vessels.

72 In the field of ship to ship LNG bunkering risk assessment, Zha (2019) completed
73 a study to assess the operational risk of LNG bunkering ship by combining Formal
74 Safety Assessment and Interval AHP. Gao (2023) used Hierarchical Task Analysis and
75 the IDAC (Information, Decision, and Action in Crew context) model to identify and
76 quantify the RIFs of human factors in LNG bunkering operations. In the field of LNG
77 leakage research, Zhang *et al.*, (2010) analysed the process of accidents such as fire and
78 explosion caused by leakage during LNG storage and transportation. The study
79 developed visualised leakage consequence analysis software based on Gaussian model.

80 Yu and Dai (2007) carried out a systematic analysis of the causes of storage tank
81 explosion and fires. The study established a fault tree, taking storage tank explosions
82 and fires as top events. Then, by applying a quadratic calculation method to the
83 structural importance coefficients of bottom events, the study located the main RIFs of
84 storage tank safety. Furthermore, Yan (2018) carried out a quantitative analysis of
85 bunkering operation accidents and constructed an LNG fuel leakage model using
86 PHAST software.

87 In summary, there are well-established methods that can be used to address
88 uncertainty in the risk assessment process. However, in the field of risk assessment for
89 ship to ship LNG bunkering, most of the current studies assess the operational safety of
90 LNG bunkering ships from a macro perspective or extrapolate the consequences of fuel
91 leakage incidents. Meanwhile, since the most serious consequence of an accident during
92 the bunkering operation is the leakage of LNG fuel, which may lead to greater hazards
93 (Chen, 2022), relatively few studies have been conducted to evaluate this critical event
94 as an objective. Therefore, as an emerging technology, the risk assessment of ship to
95 ship LNG bunkering needs to be explored more thoroughly by combining the existing
96 advanced assessment methods.

97 Therefore, based on related research, this study develops a new risk assessment
98 model to solve the problem of existing uncertainties. This study is able to the
99 quantification and ranking of RIFs leading to the safety of ship to ship LNG bunkering,
100 which improves the safety of ship to ship LNG bunkering operations. The main
101 contributions and innovations of this study as shown below.

102 (1) From the process of ship to ship LNG bunkering operations, the RIFs of "ship
103 to ship LNG bunkering fuel leakage" are identified on the basis of relevant research,
104 which can be used to identify risks affecting operational safety.

105 (2) FBRBN and ER algorithms are introduced to address research data limitations
106 and expert knowledge uncertainties. By employing the strengths of FMEA, FBRBN,
107 AHP, ER and utility functions, a model for risk assessment is proposed.

108 (3) In order to validate the established risk assessment model, the ship to ship LNG
109 bunkering operation near Zhoushan LNG emergency anchorage is used as a case study.

110 The results of the study show that the established assessment model has good rationality
 111 and applicability, and the quantitative indicators affecting the risk events of ship to ship
 112 LNG bunkering have been clarified with the help of this case study.

113 (4) Based on the results of the study, the RIFs for the safety of ship to ship LNG
 114 bunkering are analysed and corresponding preventive and control measures are
 115 proposed.

116 **RIFs System of Ship to Ship LNG Bunkering Fuel Leakage**

117 In order to improve the current research, it is necessary to establish a reasonable
 118 framework for RIFs. Considering the relative complexity of the risk research system of
 119 ship to ship LNG bunkering, it is necessary to fully understand the associated attributes
 120 and the influence of each RIF when building the framework system. Therefore, this
 121 study constructs a RIFs system for ship to ship LNG bunkering fuel leakage from its
 122 operational process, with reference to related studies, taking "ship to ship LNG
 123 bunkering fuel leakage" as the evaluation objective.

124 **Ship to ship LNG bunkering process**

125 According to the Accident Causation Theory (Lehto and Salvendy, 1991), the
 126 subjects involved in ship to ship LNG bunkering operations all have an impact on the
 127 safety of the operation. Different RIFs can occur in different parts of the bunkering
 128 operation. Therefore, it is feasible to specify the RIFs of different subjects in
 129 chronological order from their operation process.

130 The operational process of ship to ship LNG bunkering consists of three main
 131 components, including berthing before the start of the operation, fuel bunkering during
 132 the operation and departure after the completion of the operation, as shown in **Table 1**.

133
 134

TABLE 1. Ship to ship LNG bunkering process.

	I Berthing	II Fuel Delivery	III Departure
Assignment content	LNG bunkering ship and LNG receiving ship berth with each other.	Filling line docking Inspection of detection and alarm systems Pre-cooling and inerting LNG fuel bunkering De-filling lines and monitoring system	LNG bunkering ship and LNG receiving ship depart.

135

136

137 **Establishment of RIFs systems**

138 According to General System Theory (Bertalanffy, 1950), a reasonable RIFs
139 framework should follow the principles of systematicity, scientificity, operability and
140 practicality. During the period of ship to ship LNG bunkering operations in **Table1**,
141 RIFs are classified into three aspects: "improper handling by personnel", "ship
142 equipment failure" and "poor environmental conditions".

143 (1) Improper handling by personnel

144 At present, the relevant operation norms and technical standards of ship to ship
145 LNG bunkering are not clear enough, resulting in the professional quality of operators
146 varying.

147 (2) Ship equipment failure

148 The communication, mooring and bunkering equipment of the LNG bunkering
149 ship and the LNG powered ship are not kept in the best condition during the bunkering
150 operation.

151 (3) Poor environmental conditions

152 Ship to ship LNG bunkering operations are often carried out in harbours,
153 anchorages and other locations, with a high density of ships and a complex environment.
154 The RIFs affecting the safety of ship to ship LNG bunkering operations are complicated.

155 On the basis of the above discussion, with reference to the ship to ship LNG
156 bunkering fuel leakage fault tree constructed by the previous study (Lyu *et al.*, 2022),
157 omitting the logical gate expressions and maintaining the hierarchical and indicator
158 correspondence, the RIFs system is established as shown in **Table 2**.

159
160

TABLE 2. RIFs of fuel leakage during ship to ship LNG bunkering.

RIFs of level I	RIFs of level II	RIFs of level III
Improper handling by personnel	Simultaneous with other hazardous operations	Simultaneous barging operations
		Multi-ship bunkering operations
	Faulty bunkering operations	Personnel unwell
		Irregularities in pipe connections
		Poor operational cooperations
		Inadequate staff training
		Incomplete purge after bunkering

	Passing ships failing to avoid effectively	Absence without leave Failure to maintain a regular lookout Poor seamanship
	Mooring failure	Cable breakage Cable reel malfunction Bump pad offset Dragging anchor
Ship equipment failure	Breakage of bunkering equipment	Pipeline corrosion Wear loss at joints Overpressure of storage tanks
	Poor communication equipment	Unstable signal transmission Low battery on intercom
Poor environmental conditions	Poor weather and sea conditions	Excessive wind and waves Poor visibility
	Discomfort in the navigable environment	Heavy traffic flow Ship wave impact

161

162 **Risk modelling based on FBRBN and ER**

163 **Risk parameters setting based on FMEA**

164 Risk is a complex concept, which requires that risk assessments be carried out
165 taking into account not only the likelihood of a catastrophic event occurring, but also
166 the associated consequences. The RIFs of ship to ship LNG bunkering are intricate and
167 coupled with each other, and it is unscientific to judge the risk only from the frequency
168 of accidents. As a systematic approach, FMEA can identify known and potential failure
169 models. Therefore, it is frequently utilised in reliability engineering as a powerful tool
170 for assessing the potential failure risk level of a product. For example, Liu and Li (2021)
171 proposed an enhanced FMEA model that takes into account the bounded rational
172 behaviour of experts and expert group, so as to enable the investigation and analysis of
173 potential failure mode risks of green logistics in cold chain; Shafiee and Animah (2022)
174 put forward an integrated risk management framework which utilises the FMEA
175 approach alongside a hybrid Multi-Criteria Decision Analysis model. The framework
176 aims to evaluate risks and prioritise mitigation strategies for subsea facilities in high
177 pressure/high temperature environments throughout their extended lifespan. To sum up,
178 FMEA is one of the most popular risk assessment methodologies due to its visibility
179 and ease of use (Yang and Wang, 2015). In this study, referring to the idea of FMEA,

180 three risk parameters are set: the likelihood of occurrence (L), the severity of
 181 consequences (C), and the probability of non-detected risk (P). In order to achieve
 182 higher parameter identification, five evaluation levels are established for each risk
 183 parameter, the explanation of fuzzy variables corresponding to each evaluation level
 184 are shown in **Table 3**.

185 **TABLE 3. Risk parameter evaluation grades and meanings.**

Risk Parameters	Evaluation Grades	Fuzzy Variables
The likelihood of occurrence (L)	L_1	Very low
	L_2	Relatively low
	L_3	General
	L_4	Relatively high
	L_5	Very high
The severity of the consequences (C)	C_1	Can be ignored
	C_2	Not serious
	C_3	Medium
	C_4	Serious
	C_5	Disastrous
The probability of non-detection of risk (P)	P_1	Very unlikely
	P_2	Unlikely
	P_3	Normal
	P_4	More likely
	P_5	Very likely

186

187 Since the current practice of ship to ship LNG bunkering is still in its infancy, there
 188 is a lack of necessary data support for assessing the accident frequency in bunkering
 189 operations. Thus, an expert investigation method is adopted to conduct expert
 190 evaluation information consultation and investigation on RIFs of level III in **Table 2**.
 191 This survey invites 25 experts from maritime authorities, universities, and shipbuilding
 192 and operating companies. The job categories include managers, researchers, and
 193 operators with relevant operating experience of LNG onshore bunkering, ship to ship
 194 LNG bunkering, LNG loading and unloading and other navigation safety work. The
 195 experts have been engaged in research or practical application in the corresponding
 196 field for 5 years or more. The experts interviewed used a five-point Likert scale to
 197 express the belief level of RIFs, which sums to 1 for each RIFs value.

198 **Reasoning of risk states based on FBRBN**

199 In the survey to elicit expert opinion on RIFs, the uncertainty in the entire event is

200 particularly acute. The main reasons include the ambiguity of the risk parameters
201 defined by the semantic criteria, the incompleteness of the information data and the
202 randomness of the assessment process. Therefore, when processing expert scoring data,
203 uncertainty evaluation methods can be used to avoid reliance on accident data and to
204 obtain more accurate assessment results.

205 The classical FMEA method has certain shortcomings, including inadequate
206 quantification of the effectiveness of preventative measures (Cui *et al.*, 2023). To
207 address these limitations, many new approaches including Markov model, grey theory,
208 Bayesian network and fuzzy logic have been suggested (Xia *et al.*, Forthcoming). As
209 an effective method in this study, BBN is utilized to depict the inference system
210 between the input (L, C, and P) and output variable R (risk status) (Yang *et al.*, 2008).
211 However, the subtle changes in linguistic variables within the antecedent attribute are
212 not necessarily reflected in traditional Fuzzy Belief Rule (FBR) systems, due to the fact
213 that their results are usually the result of a single output. In view of this, the ability of
214 rule base to deal with uncertainty in a complex system can be improved by
215 incorporating the notion of Belief Degree. For example, Wan *et al.*, (2019) introduced
216 a new model for evaluating the RIFs of maritime supply chains, which utilises a fuzzy
217 belief rule approach combined with BN. Yang *et al.*, (2009) proposed a subjective
218 security-based assessment and management framework using fuzzy ER approaches by
219 introducing the concept of degree of belief, which can be utilized to collate and analyze
220 subjective risk assessment data pertaining to various aspects of a maritime
221 transportation system from numerous experts in a systematic way. The regulations
222 within the belief rule base are expressed by taking the shape of conditional probability
223 to realize rule fusion. As a result, the new method can solve the problem of ambiguity
224 and incompleteness effectively in uncertain systems by modelling the relationship
225 between input conditions and output results, presenting the output results in the form
226 of a belief distribution.

227 In this study, the experts use a five-point Likert scale to express the belief level of
228 a risk parameter for each RIFs in level III, which sums to 1 for any risk parameter. In
229 the meanwhile, risk parameters *L*, *C*, and *P* reflect different evaluation aspects of RIFs,

230 and their weight differences largely affect the accuracy of quantitative evaluation of
 231 risk events. In view of the fact that there are few related studies in the field of risk
 232 assessment of ship to ship LNG bunkering, the same method of scoring by the
 233 interviewed experts is adopted to determine the weight of L , C and P . Each expert is
 234 given the same weight, i.e., an arithmetic mean is used to calculate the experts' scores
 235 for L , C , and P . After processing, the values of L , C , and P are determined as 0.18, 0.74,
 236 0.08. Then there are 125 (5^3) rules in total for the FBR established in this study.

237 BN is one of the most effective conceptual networks for knowledge representation
 238 and inference research under uncertainty due to its advantages in expressing non-linear
 239 relationships (Cao *et al.*, 2023a). Thus, BN can be used to synthesize belief distributions
 240 for various rules. Therefore, through modelling of BN, the FBR base can be
 241 transformed in to a BN with several parent nodes and one sub-node. The information
 242 from the processed expert evaluations of the risk parameters can be used as the prior
 243 probability of each parent node, and the process of calculating the marginal probability
 244 of a sub-nodes is simplified by a belief rule-based risk inference process. On this basis,
 245 the marginal probability of sub-node can be obtained according to Eq. (1)

$$246 \quad p(R_h) = \sum_{i=1}^I \sum_{j=1}^J, \dots, \sum_{k=1}^K p(R_h | A_i, B_j, \dots, C_k) p(A_i) p(B_j), \dots, p(C_k) \quad (1)$$

247 where A, B, \dots, C are the input conditions of the FBR; I, J, \dots, K are the number of
 248 reference values of each input condition; $p(A_i)$ is the probability that input condition
 249 A takes the i^{th} rank; $P(R_h)$ is the probability that risk state R is the h^{th} rank.

250 **Aggregation of risk states based ER**

251 In the survey on RIFs system conducted by the expert research method, only the
 252 scores of experts on RIFs in level III are collected due to the fact that the RIFs in level
 253 I and II are extensive and difficult to quantify. At this point, the risk data for levels I
 254 and II are missing, so it is necessary to deduce the risk status of the upper levels based
 255 on the risk status of level III, which is to complete the process of data aggregation.
 256 Before data aggregation, it is necessary to determine the weight of the RIFs in the upper
 257 level to the lower level.

258 Due to its extreme applicability, AHP is widely used in green port development

259 evaluation (Wan *et al.*, 2018). For examples, Loughney *et al.*, (2021) utilized multi-
260 attribute decision analysis and AHP methods to identify optimal locations for floating
261 offshore wind farms along Scotland's northern coast; Yang *et al.*, (2018) investigate
262 climate change adaptation measures in ports with high data uncertainty by combining
263 fuzzy Bayesian risk analysis approaches, AHP and ER methods. AHP is proposed as a
264 method for expressing and addressing individuals' subjective judgements in a
265 quantitative form and is frequently implemented in making decisions involving
266 multiple plans or objectives. Utilising the already established hierarchy of RIFs, the
267 method makes use of less quantitative information in mathematising the decision-
268 making process and serves as a potent technique for tackling intricate problems having
269 multiple plans or objectives.

270 **Table 2** expands the RIFs leading to ship to ship LNG bunkering fuel leakage in
271 the form layers. The occurrence of lower-level RIFs will lead to the occurrence of
272 upper-level RIFs, which will further lead to the occurrence of top incidents. The AHP
273 method compares the lower-level RIFs contained in the upper level using a 1-9 scale
274 method pairwise comparison, from this, the judgment matrix is constructed, so that the
275 relative weight of the RIFs under a single criterion can be used to determine the weight
276 of the indicators at different levels.

277 More recently, risk assessment of ship to ship LNG bunkering has seen a shift in
278 research priorities. Due to the imprecise and incomplete nature of available data, the
279 focus has moved from strictly quantifying probabilities and consequences to
280 incorporating both accurate and uncertain information to better quantify risks (Ruponen
281 *et al.*, 2022). During the process, the ER methodology has demonstrated its benefits in
282 addressing incompleteness and uncertainties, especially in relation to Likert-based
283 rating sets (Chang *et al.*, 2021). Combining AHP method, ER completes the aggregation
284 of risk states by evaluating the results of RIFs at the lower level to obtain the risk states
285 of RIFs at the upper level. The process is represented as follows:

286 The risk state of RIF A is assumed to be R_A , the risk state of RIF B is R_B , and the
287 output risk state of both is R_{AB} , which can be obtained by aggregation. Each of the above
288 3 sets contains 5 levels, denoted as:

289 $R_A = \{(R_1, \beta_A^1), (R_2, \beta_A^2), (R_3, \beta_A^3), (R_4, \beta_A^4), (R_5, \beta_A^5)\}$

290 $R_B = \{(R_1, \beta_B^1), (R_2, \beta_B^2), (R_3, \beta_B^3), (R_4, \beta_B^4), (R_5, \beta_B^5)\}$

291 $R_{AB} = \{(R_1, \beta^1), (R_2, \beta^2), (R_3, \beta^3), (R_4, \beta^4), (R_5, \beta^5)\}$

292 where β is the distribution of belief levels for different levels of risk states.

293 During the risk assessment process, the normalised weights of RIFs A and B are
 294 called ω_A and ω_B ($\omega_A + \omega_B = 1$). The weighted belief parameters M_A^m and M_B^m are
 295 defined by the data sets of R_A and R_B . Its expression is as shown in Eqs. (2) and (3).

296
$$M_A^m = \omega_A \beta_A^m \quad (2)$$

297
$$M_B^m = \omega_B \beta_B^m \quad (3)$$

298 where m is the number of risk status level ($m = 1, 2, 3, 4, 5$).

299 Assuming H_A and H_B as the belief levels not yet assigned to M_A^m and M_B^m , the
 300 expressions are shown in Eqs. (4) and (5).

301
$$H_A = \overline{H}_A + \tilde{H}_A \quad (4)$$

302
$$H_B = \overline{H}_B + \tilde{H}_B \quad (5)$$

303 where \overline{H}_n ($n = A, B$) is the influence parameter for other RIFs; \tilde{H}_n ($n = A, B$) is the
 304 information incompleteness parameter for R_A and R_B .

305 The relationship between the above parameters is expressed as Eqs. (6)-(9):

306
$$\overline{H}_A = 1 - \omega_A \quad (6)$$

307
$$\overline{H}_B = 1 - \omega_B \quad (7)$$

308
$$\tilde{H}_A = \omega_A (1 - \sum_{m=1}^5 \beta_A^m) \quad (8)$$

309
$$\tilde{H}_B = \omega_B (1 - \sum_{m=1}^5 \beta_B^m) \quad (9)$$

310 Then, the weighted belief parameter $\beta^{m'}$ after aggregation of R_A and R_B is
 311 calculated in Eq. (10):

312
$$\beta^{m'} = K(M_A^m M_B^m + M_A^m H_B + M_B^m H_A) \quad (10)$$

313 The incompleteness parameters after aggregation of R_A and R_B are calculated as
 314 Eqs. (11)-(12):

315
$$\overline{H}'_U = K(\overline{H}_A \overline{H}_B) \quad (11)$$

316
$$\tilde{H}'_U = K(\tilde{H}_A \tilde{H}_B + \tilde{H}_A \overline{H}_B + \tilde{H}_B \overline{H}_A)$$
 (12)

317 where K is the normalization factor and its expression is shown as Eq. (13):

318
$$K = \left(1 - \sum_{s=1}^5 \sum_{\substack{t=1 \\ t \neq s}}^5 M_A^s M_B^t \right)^{-1}$$
 (13)

319 At the end of the R_A and R_B aggregation operation, the new belief distribution of
 320 the original data is obtained by redistributing the belief levels in the incompleteness
 321 parameter \overline{H}'_U to each level in the output risk state set, calculated in Eqs. (14)-(15):

322
$$\beta^m = \frac{\beta^m}{1 - \overline{H}'_U}$$
 (14)

323
$$H_U = \frac{\tilde{H}'_U}{1 - \overline{H}'_U}$$
 (15)

324 In the Eqs. (14)-(15), β^m is the combined belief distribution of the aggregation
 325 results and H_U is the belief level of incompleteness of the aggregation process.

326 The above is the calculation process of aggregation of two pieces of evidence
 327 information. ER operation is in accordance with the law of exchange and the law of
 328 combination. When aggregating multiple risk state belief distribution data, any two
 329 aggregation can be performed first, and then the sequential operation is performed to
 330 finally get the aggregation results.

331 **Quantification of RIFs**

332 In order to translate the belief distribution of risk states into a numerical expression,
 333 the concept of utility values $U(R_h)$ is introduced and the utility values of the different
 334 levels of risk states are linearly assigned as: $UR1 = 1^3 = 1$, $UR2 = 2^3 = 8$, $UR3 = 3^3 = 27$,
 335 $UR4 = 4^3 = 64$, $UR5 = 5^3 = 125$.

336 The risk priority value index (RPI) can realise the quantification of RIFs, this
 337 process is realised by using the linear effect function. The specific calculation process
 338 is Eq. (16).

339
$$RPI = \sum_{h=1}^5 p(R_h) \times U(R_h)$$
 (16)

340 **Validation**

341 After finishing the modelling, it is crucial to verify its dependability. In this study,
342 a sensitivity analysis of the results is performed using an axiom-based validation
343 process. A reasonable model should satisfy the following 3 axioms (Wang *et al.*, 2023).

344 Axiom 1: Changing each parent node's prior probability will undeniably result in
345 a proportional shift in its sub/target node's posterior probability.

346 Axiom 2: When the subjective probability distribution of the parent node changes,
347 the degree to which different parent nodes influence the value of the sub-node ought to
348 be commensurate with the weight of parent node.

349 Axiom 3: The impact of the set of risk parameters on *RPI* should always surpass
350 the impact of alterations in any arbitrary subset on the *RPI* value.

351 **Case study**

352 **Quantification of risk status**

353 Zhoushan Port is one of the major port hubs in China, located in the north-east of
354 Zhoushan Island. Xinao Zhoushan LNG receiving terminal is a comprehensive project
355 that combines LNG storage and transshipment and ship bunkering with a number of
356 other businesses and functions. Considering that it is located near an important shipping
357 route between northern and southern China, comprehensive identification and
358 quantification of bunkering risks can improve the quality of operators and build a risk
359 prevention and control system to ensure operational safety.

360 In this section, the ship to ship LNG bunkering operation near the LNG emergency
361 anchorage in Zhoushan is selected as the research object. A case study is conducted to
362 apply the FBRBN, AHP and ER methods to develop an in-depth quantitative analysis
363 of the RIFs leading to fuel leakage accidents during ship to ship LNG bunkering
364 operations under uncertain conditions. It also can test the feasibility and practicality of
365 the above research methods. Furthermore, a total of 25 experts, all from the field of ship
366 to ship LNG bunkering and related fields, are invited to this study. The experts are
367 invited to evaluate the Level III RIFs that contribute to fuel leakage in **Table 2**, using a
368 Likert scale. The experts also scored the weights of *L*, *C*, *P* on a 1-9 scale for the lower-

369 level RIFs contained in the upper level. In collating these three parts of the data, the
 370 same weights are given to the experts, i.e., the data are treated as arithmetic means.

371 After obtaining the belief ratings for the risk parameters from experts of the RIFs
 372 in Level III of the system, the experts are given the same weight in the process of
 373 combining their evaluations in order to reflect the generality of the data. Since L , C and
 374 P have 5 levels of evaluation, R is also divided into 5 levels from "very good" to "very
 375 poor" and is set from R_1 to R_5 . Through equation (1), the risk states of the level III RIFs
 376 can be calculated. Taking the RIF "Cable reel malfunction" as an example, the value of
 377 the RIF is calculated:

378
$$p(R_h) = (13\%, 36\%, 24\%, 21\%, 6\%)$$

379 The result means there is a 13% probability of R_1 , a 36% probability of R_2 , a
 380 24% probability of R_3 , a 21% probability of R_4 and a 6% probability of R_5 . The reasoning
 381 process can be demonstrated by using the Bayesian modeling software GeNIe 2.0, as
 382 shown in Figure 1.

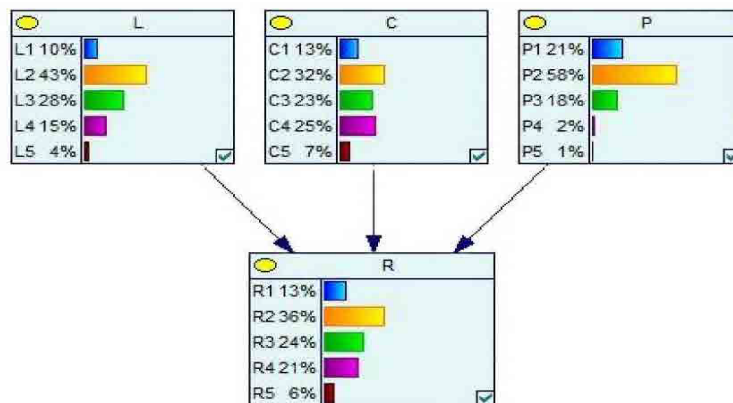


FIG. 1. Risk reasoning process on "mooring winch break down"

383

384 Likewise, the risk states of all RIFs from level III in the system can be obtained.
 385 This completes the reasoning of the bottom-level RIFs from risk states to risk
 386 parameters. In this expert research, AHP is used to collect the weight scores of experts
 387 on the RIFs of the lower-level included in the upper-level and complete the relevant
 388 calculations. A 1-9 scale is used to compare the RIFs on a two-by-two basis and to give
 389 importance assignments. This completes the calculation of the relative weight scores of
 390 the RIFs in level II and III of the system by different experts, and the evaluation results
 391 of the relative weights are also obtained in the form of arithmetic averages, as shown

392 in **Table 4**.

393
394

TABLE 4. Relative weights of RIFs at level II and III.

RIFs of level II			Relative weights	RIFs of level III		Relative weights
Simultaneous hazardous operations	with other	0.113		Simultaneous barging operations	0.208	
				Multi-ship bunkering operations	0.792	
Faulty bunkering operations		0.657		Personnel unwell	0.101	
				Irregularities in pipe connection	0.397	
				Poor operational cooperation	0.090	
				Inadequate staff training	0.146	
Passing ships failing to yield effectively		0.230		Incomplete purge after bunkering	0.266	
				Absence without leave	0.560	
				Failure to maintain a regular lookout	0.328	
Mooring failure		0.312		Poor seamanship	0.112	
				Cable breakage	0.311	
				Cable reel malfunction	0.174	
				Bump pad offset	0.177	
Breakage of bunkering equipment		0.586		Dragging anchor	0.338	
				Pipeline corrosion	0.120	
				Wear loss at joints	0.278	
Poor communication equipment		0.102		Overpressure of storage tanks	0.602	
				Unstable signal transmission	0.357	
Poor weather and sea conditions		0.617		Low battery on intercorn	0.643	
				Excessive wind and waves	0.567	
Discomfort in the navigable environment		0.383		Poor visibility	0.433	
				Heavy traffic flow	0.483	
				Ship wave impact	0.517	

395

396 And then, the risk states of all RIFs in the system level I and level II are obtained
397 using the evidential reasoning method. Finally, using equation (16), the quantification
398 of the risk status of all RIFs in the system is completed, as shown in **Table 5**.

399

TABLE 5. Comprehensive sequencing of fuel leakage RIFs during ship to ship LNG bunkering.

RIFs of level I	RPI	Rank	RIFs of level II	RPI	Rank	RIFs of level III	RPI	Rank
Improper handling by personnel	69.84	1	Faulty bunkering operations	71.10	1	Inadequate staff training	89.48	1
						Personnel unwell	79.95	2
						Irregularities in the pipe connections	76.50	3
						Poor operational cooperations	58.28	8
						Incomplete purge after bunkering	44.61	13
			Passing ships failing to avoid effectively	64.04	2	Absence without leave	66.38	4
						Failure to maintain a regular lookout	60.27	6
						Poor seamanship	38.66	16
						Multi-ship bunkering operations	55.07	9
						Simultaneous barging operations	49.19	10
Simultaneous with other hazardous operations	55.26	4	Poor weather and sea conditions	61.69	3	Excessive winds and waves	62.49	5
						Poor visibility	59.33	7
						ship wave impact	48.54	11
						Heavy traffic flow	37.47	17
Discomfort in the navigable environment	42.87	5	Breakage of bunkering equipment	42.17	6	Wear loss at joints	47.71	12
						Overpressure of storage tank	42.03	14
Ship equipment failure	38.90	3	Mooring failure	34.83	7	Pipeline corrosion	29.40	21
						Cable breakage	40.88	15
						Dragging anchor	37.08	18
			Poor communication equipment	27.72	8	Cable reel malfunction	30.43	20
						Bump pad offset	24.67	22
						Low battery on intercom	31.88	19
			Unstable signal transmission	19.26	23			

400

401

402

403 **Validation**

404 The three axioms in section Validation above will be applied to validate the
405 robustness of the model in the risk assessment of ship to ship LNG bunkering. Taking
406 the RIF "Cable reel malfunction" as an example, in order to avoid possible deviations
407 due to expert judgement and missing data, the findings from the model analysis are
408 compared to verify the correctness and validity of the model developed.

409 In this case, there is a positive correlation between the *RPI* value of the RIF and
410 the probability values of the three risk parameters. For example, the closer the
411 likelihood of occurrence *L* is to "very high L_5 ", the closer the severity of consequences
412 *C* is to "disastrous C_5 ", the closer the probability of non-detection risk *P* is to "very
413 likely P_5 ", the closer the risk status *R* is to "very poor R_5 ", and the higher the *RPI* value
414 of the RIF is. In the RIF "cable reel malfunction", for likelihood of occurrence *L*, the
415 subjective probability of 0.1 is redistributed to different levels on the basis of the
416 original model in a way that maximises the increase in the *RPI* value. When the
417 subjective probability of L_1 decreases by 0.1 and the subjective probability of L_5
418 increases by 0.1, the *RPI* value increases from 30.43 to 32.91. The process of testing
419 the severity of consequences *C* and probability of non-detection risk *P* is the same. Such
420 an analytical approach is applied to other RIFs at the level III of system to examine the
421 impact of changes in subjective probability distributions of any of the three risk
422 parameters on the *RPI* values. The results are in accordance with axiom 1. No outliers
423 in the magnitude of change in *RPI* values, which indicates that the FBRBN
424 methodology used in the present case has strong logic and consistency.

425 The above test results demonstrate the sensitivity of the model to discrete changes.
426 Similarly, it is necessary to carry out a sensitivity analysis of continuous changes. For
427 each risk parameter, the subjective probability of 0.02 is reallocated each time with the
428 largest increase in the *RPI* value. The incremental change in the *RPI* value is examined
429 for the subjective probability of change interval in the incremental process of [0, 0.1].
430 Taking RIF "cable reel malfunction" as an example, the calculation results are shown
431 in Figure 2. It can be seen by comparison that the degree of influence of changes in the

432 probability values of different risk parameters on the *RPI* value is significantly different.
 433 But, the degree of influence is always proportional to the weights of the three risk
 434 parameters *L*, *C* and *P* ($L: C: P = 0.18: 0.74: 0.08$). Similarly, the other RIFs at level III
 435 are all in line with the above regular characteristics. Therefore, the test results are in
 436 line with axiom (2), indicating that the FBRBN method used in this case has good
 437 robustness.

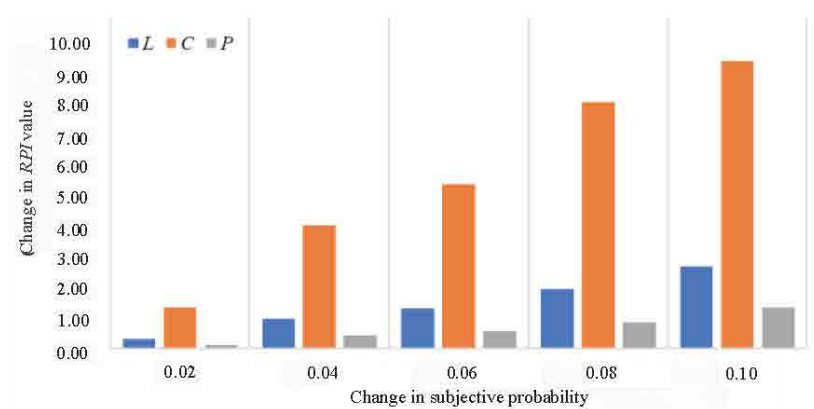


FIG.2.Sensitivity analysis on the influence of various probability value of risk parameters

438
 439 Finally, the effect of combinations of changes in the probability values of the risk
 440 parameters on the *RPI* values is examined by dividing the three risk parameters into
 441 seven possible combinations. The number of risk parameters for reallocating subjective
 442 probabilities are 1,2 and 3 respectively, category 1 considers only the change in the
 443 probability value of one risk parameter. Category 2 considers the combinations of the
 444 changes in the probability values of the two risk parameters. Category 3 considers the
 445 change in the probability values of all the three risk parameters in the third category.
 446 Still taking the RIF "cable reel malfunction" as an example, for each risk parameter, the
 447 subjective probability of 0.1 is redistributed in different classes in the way to increase
 448 *RPI* value the most, and the corresponding results of the change in *RPI* value are shown
 449 in **Table 6**.

TABLE 6. The influence of various risk parameter combinations on *RPI*.

Portfolios	Risk parameter			RPI value	Amount of RPI change
	<i>L</i>	<i>C</i>	<i>P</i>		
#1	O			32.91	2.48
#2		O		39.11	8.68
#3			O	31.67	1.24
#4	O	O		41.59	11.16

#5	O		O	34.15	3.72
#6		O	O	40.35	9.92
#7	O	O	O	42.83	12.40

“O” denotes the selection of items for different combinations of risk parameter variations.

451

452 By comparing the data in the **Table 6**, it is possible to determine the relationship
453 between the magnitude of the effect of the varying combinations of probability values
454 of different risk parameters on the *RPI* values. Taking portfolio #4 as an example, the
455 amount of changing *RPI* value corresponding to this portfolio is 11.16 (41.59-30.43).
456 The subsets of this portfolio are portfolio #1 and #2 respectively, with the amount of
457 change in *RPI* value 2.48 (32.91-30.43) and 8.68 (39.11-30.43) respectively, which is
458 less than 11.16, and conforms to axiom (3). Similarly, comparative analyses can be
459 carried out between other RIFs and other combinations of the level III RIFs, and the
460 results of the tests are all in accordance with axiom (3), indicating that the FBRBN
461 method used in this case is sufficiently reliable and reasonable.

462 **Analysis of results**

463 It can be seen from **Table 5** that the comprehensive risk degree of RIFs of ship to
464 ship LNG bunkering fuel leakage level I in this case is "improper handling by
465 personnel", "poor environmental conditions" and "ship equipment failure". Based on
466 the above three aspects, this study conducts an in-depth analysis of RIFs with high *RPI*
467 values, explores the causes of the problem, and proposes corresponding security
468 measures.

469 The RIF with the highest risk priority in level I is "Personnel Unwell", which has
470 the highest *RPI* of 69.84. Among the level III of RIFs, the *RPI* values of "inadequate
471 staff training", "personnel unwell", "irregularities in pipe connections" are as high as
472 89.48, 79.95, and 76.50, ranking the top 3 RIFs and are the main RIFs affecting the
473 safety of ship to ship LNG bunkering. And these RIFs all belong to the level II RIF
474 "Faulty bunkering operations". This is because the ship to ship LNG bunkering
475 operation is still in its infancy, and the training of operators and related technical
476 standards are not perfect. Therefore, the training and assessment of the staff engaged in
477 ship to ship LNG bunkering operation should be strengthened. A rigorous selection and

478 elimination mechanism should be set up to select crew members with high
479 professionalism to be in charge of the operation. Relevant training departments should
480 fully understand the high risk of ship to ship LNG bunkering operation to optimise the
481 theoretical curriculum and practical assessment mode. Law enforcement departments
482 should also strengthen inspection and supervision. Meanwhile, if the operator is found
483 to be physically incapable of fulfilling the job requirements, the bunkering operation
484 should be stopped immediately and a suitable replacement should be arranged. The
485 LNG bunkering ship and the LNG-powered ship should make sure that both sides can
486 accurately understand each other's division of labours, so as to perform their respective
487 duties and work closely together.

488 Poor environmental conditions in level I have the second highest *RPI* value of
489 56.66. The *RPI* values for excessive wind and waves and poor visibility are relatively
490 high, which are also classified as severe weather and sea conditions in level II. This is
491 due to the climate characteristics of Zhoushan sea area: Zhoushan harbour has abundant
492 rainfall. During the fishing moratorium, there will be occasional bad weather and sea
493 conditions such as sea fog, thunderstorms and even typhoons. Thus, the natural
494 environmental conditions need to be paid more attention. In the process of ship to ship
495 LNG bunkering operation, both the bunkering ship and the recipient ship should do:

496 Ships need to pay attention to the natural environmental conditions in real time
497 and make early prediction. The weather forecast or weather fax map issued by the
498 weather station in time need to be received to make all preparations. If it is found that
499 the operation area is about to encounter or is encountering the catastrophic weather such
500 as "excessive wind and waves", the operation should be stopped immediately and take
501 effective collision avoidance measures decisively.

502 Bunkering operations in "poor visibility" conditions should correctly display lights
503 according to the regulations of the sound horn. Operators should closely observe the
504 changes in the farthest visibility distance. Radar, VHF, AIS and other navigational aids
505 need to be used correctly, crew also need be aware of ship dynamics in time. If it is
506 necessary, crew should timely report to the VTS centre and seek the assistance of
507 maritime management agencies to implement traffic control.

508 Ship equipment failure in level I has the lowest *RPI* value of 38.90. Among them,
509 the *RPI* values of “unstable signal transmission”, “Bump pad offset”, and “pipeline
510 corrosion” are the lowest, indicating that their comprehensive impact on the safety of
511 ship to ship LNG bunkering is relatively small. This is also related to the fact that both
512 LNG bunkering ships and LNG powered ships meet relatively high design standards.
513 Therefore, it is important for operators to enhance equipment and maintenance and for
514 maritime administrations to implement rigorous inspection regimes and standards.

515 This study will help to improve the safety level of ship to ship LNG bunkering
516 operations, and provide reference for stakeholders in the formulation of relevant
517 technical standards and regulations, etc. At the theoretical level, based on the
518 consideration of the impact of uncertainty on the safety assessment of ship to ship LNG
519 bunkering, this study innovatively introduces a system to identify factors that affect the
520 safety of ship to ship LNG bunkering operation and finally realises quantitative risk
521 assessment. At the practical level, the numerical value and ranking of *RPI* in this study
522 can help stakeholders understand the impact of different operating entities and RIFs on
523 operating safety. This study also provides targeted recommendations for different RIFs.
524 In view of this, in the practice of ship to ship LNG bunkering operations in the future,
525 it is necessary to standardize the operational behavior of personnel, closely monitor
526 environmental changes, and strengthen equipment maintenance.

527 **Conclusion**

528 This paper proposes a new evaluation approach for the identification,
529 quantification and ranking of ship to ship LNG bunkering RIFs. On the basis of relevant
530 research, a risk assessment model for quantitatively ranking risk events using FMEA,
531 AHP, FBRBN and ER methods is proposed. As a result, reasoning from risk parameters
532 to risk states for specific RIFs under uncertainty, aggregation operations for risk states
533 and quantitative ranking of risk values are implemented. The results of the study show
534 that "improper handling by personnel" is the most important RIFs affecting the safety
535 of ship to ship LNG bunkering. Among them, "inadequate staff training", "personnel
536 unwell" and "poor operational cooperation" are the three RIFs with the highest *RPI* in

537 the level III of the system. This study validates the efficacy of the model through a case
538 study. The results indicate a high level of robustness and practicality of the proposed
539 risk assessment model.

540 However, due to the incompleteness caused by the lack of relevant cases, the
541 ambiguity of expert evaluation opinions, and the randomness of the operating
542 environment, the limitations of this study still exist. Due to the limited number of
543 accident reports collected in this study, the interactions between the RIFs are not
544 investigated. In future research, the objective data collected in actual work cases can be
545 used to replace some of the expert scoring data in the research process of this paper, so
546 as to further improve the credibility and practicability of the relevant models.

547 **Data Availability Statement**

548 The following data supporting the results of this study are available from the
549 corresponding author upon reasonable request.

550 (1) Fuzzy belief rule base for ship to ship LNG bunkering fuel leakage risk
551 evaluation.

552 (2) Weighting evaluation and subjective probability evaluation of the processed
553 risk factors from the ship to ship LNG bunkering fuel spill questionnaire.

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