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Risk Assessment of Operational Safety for Oil Tankers - A Revised Risk Matrix

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This paper is aimed at the risk assessment of operational safety for oil tankers. Based on the operational features of oil tankers and relevant literature, the Risk Factors (RFs) of operational safety were first identified. A revised risk matrix based on a fuzzy Analytical Hierarchy Process (AHP) approach was then proposed to assess the risk classes of the RFs. Finally, to validate the research model, the oil tanker fleet of Chinese Petroleum Corporation (CPC) in Taiwan was empirically investigated. The results can provide practical information for oil carriers to improve their ships' operational safety. Furthermore, the revised risk matrix may provide a theoretical reference for methodological researches in safety risk assessments.

KEYWORDS

1. Oil tanker. 2. Risk. 3. Fuzzy AHP.

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1. INTRODUCTION. In practice, an oil tanker may either transport oil to refineries, or transport oil from refineries to oil purchasers' locations. The former is known as a crude oil tanker, whereas the latter is a product oil tanker. An oil tanker can carry anywhere from around 1,100 tons for product oil tankers to over 550,000 tons for ultra large crude oil tankers. Due to carrying large amounts of oil, an oil tanker accident may cause large oil spills. In addition to economic losses, this may result in environment pollution, leading to damage to ecosystems. Thus, oil tankers' safety issues require close attention.

To improve the safety of oil tankers, exploring the determining factors of marine accidents is necessary. In the relevant literature, many determining factors have been proposed, including human factors (e.g. Hetherington et al., 2006), safety management (e.g. Havold, 2010), navigation errors (e.g. Ismail and Karim, 2013) and the natural environment (e.g. Ismail and Karim, 2013). However, most of those studies focused on post event investigations. In practice, the concept of advance prevention should be more important. An adequate preventative measure can reduce accidents and save losses for organisations (Kontovas and Psaraftis, 2009).

For advance prevention, risk assessment of accidents is the initial and often the most important step (Chang et al., 2014). For improving maritime safety, the International Maritime Organization (IMO) developed a Formal Safety Assessment (FSA) framework to reduce the risks of marine accidents (IMO, 2013). FSA is a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of the IMO's options for reducing these risks (Psaraftis, 2012). In the FSA process, a risk matrix is the main analysis tool for risk assessment of accidents. A risk matrix displays the basic properties, "consequence" and "likelihood" of an adverse Risk Factor (RF) and the aggregate notion of risk by means of a graph (Duijm, 2015). In the traditional risk matrix, both the consequence and likelihood are measured by a category scale such as negligible, serious and catastrophic for the consequence measurement and almost impossible, probable and often for the likelihood measurement. In practice, such a discrete scale measurement may limit its applications (e.g. Cox, 2008; Smith et al., 2009; Levine, 2012). Thus, to improve the performance of risk management, a risk matrix with a continuous scale may be considered (Duijm, 2015).

This paper is aimed at the risk assessment of operational safety for oil tankers. Specifically, this paper proposes a revised risk matrix with a continuous scale to assess the risk. In this paper, based on the FSA framework, the RFs of operational safety for oil tankers are first identified. A fuzzy Analytical Hierarchical Process (AHP) model is then conducted to weight those RFs, by which the revised risk matrix is constructed to classify the RFs. Finally, the Chinese Petroleum Corporation (CPC) oil tanker fleet in Taiwan is empirically investigated to validate the research model. The rest of this paper is organized as follows. Section 2 explains the literature reviews. Section 3 describes the research method in this paper. The results are then discussed in Section 4. Finally, some general conclusions and limitations for further research are given.

2. LITERATURE REVIEW.

In this section, the traditional risk matrix is first introduced. The relevant literature related to improving the traditional risk matrix is then reviewed. Finally, for identifying the RFs of operational safety for oil tankers, the relevant studies on the safety factors of shipping operations are explored

2.1. *Risk Matrix.*

Risk is often expressed in terms of a combination of the *consequences* of an event together with the associated *likelihood* of its occurrence (ISO, 2009). Risk consequence is regarded as the loss or severity to an organisation if a risk event occurs (NPSA, 2008). Traditionally, consequence is generally described by a category scale and rated, such as "insignificant", "minor", "moderate", "major", and "catastrophic" (Chang et al., 2014). Risk likelihood is defined as the probability of the event occurring and conventionally described by a category scale. such as "rare", "unlikely", "possible", "likely" and "almost certain" (NPSA, 2008; Chang et al., 2014).

For risk assessment of an event, the risk matrix is one of the most popular tools. A risk matrix facilitates assigning a discrete risk category to each combination of consequence and likelihood (Duijm, 2015). In a traditional risk matrix with m consequence categories and n likelihood categories, one can discriminate $m \times n$ different risk categories. It is normal to divide the cell of the risk matrix in areas with fewer categories, often by using colours, such as green, yellow and red, to represent Low risk (L), Medium risk (M) and High risk (H), or by deriving a risk score based on the ordinal values of consequence and likelihood, such as the multiplication of the ordinal numbers of the likelihood and consequence category.

Likelihood \ Consequence	1	2	3	4
4	M (4)	M (8)	H (12)	H (16)
3	M (3)	M (6)	M (9)	H (12)
2	L (2)	M (4)	M (6)	M (8)
1	L (1)	L (2)	M (3)	M (4)

Figure 1. A traditional 4 × 4 risk matrix.

For example, Figure 1 is a 4 × 4 risk matrix with 16 risk categories which are classified as three types of risk scales by risk scores. The risk score for each category is shown in the parentheses. The risk categories with risk scores 1 ∼ 2 are identified as the low risk scale (L); 3 ∼ 9 as the Medium risk scale (M); 12 ∼ 16 as the High risk scale (H).

2.2. *Limitations of the traditional risk matrix.* Although the traditional risk matrix has been applied widely, there are some limitations to its practical applications. Duijm (2015) reviewed relevant studies and proposed six limitations of the risk matrix in practical applications, of which most studies focus on the following three issues:

(1) Consistency between the risk matrix and quantitative measures, and, as a consequence, the appropriateness of decisions based on risk matrices (Cox, 2008; Levine, 2012).
(2) The subjective classification of consequence and probability (Smith et al., 2009).
(3) The definition of risk scores and its relation to the scaling of the categories (linear or logarithmic) (Franks and Maddison, 2006; Levine, 2012).

To improve the above limitations, some risk matrices based on a continuous probability-consequence map were thus proposed (e.g. Meng et al., 2010; Arunraj et al., 2013; Chang et al., 2014). Differing from the traditional risk matrix, these matrices proposed continuous risk scales to identify RFs, and several nonlinear curves based on the product of the risk probability and the risk consequence are employed to divide the risk scale into three types of risks: low risk, medium risk and high risk. These risk matrices improve some limitations of traditional risk matrices. However, in these studies, chosen experts need to score each RF directly based on their subjective perceptions. In practice, this could reduce the measurement validities of the experts, leading to a decrease in the assessment performance of the risk matrix. To improve this limitation, a revised risk matrix with a continual scale based on a relatively comparable scoring system is thus proposed in this paper.

2.3. *Shipping operations safety factors.* In the relevant studies, the safety factors for shipping operations can be classified into five categories: human factor, machinery condition, ship management, organisation management and natural environment.

2.3.1. *Human factor.* In the relevant literature, most studies indicated human factors are the most significant determinant for shipping safety. For example, Hetherington et al. (2006) investigated the human effects on shipping safety. The result indicated the work safety concept originated from workers' safety knowledge, and the determinants of work safety include fatigue, stress and the work environment. Havold (2010) indicated that safety culture has significant effects on shipping safety for oil tankers which include the management styles of shipping carriers, work stresses, safety knowledge and crews' perceived fatalism. The relevant studies also indicate that crews' work characteristics including professional skills and work attitudes, significantly affect the safety of ship navigation in ports (Hsu, 2012). Crews' safety knowledge and work concentration are the most significant factors affecting the safety of product oil tankers in costal shipping (Hsu, 2015).

2.3.2. *Machinery condition.* Machinery condition is defined as the condition of a ship's machinery, facilities and equipment for work safety. Relevant studies indicated the maintenance of personal safety equipment may significantly reduce the threats to workers' safety (Gordor et al., 2005). Vessels in poor condition (Liu et al., 2006) may lead to marine disasters. Improper operation, machinery failure (Hsu, 2012; 2015), and the type, size, age and the condition of a vessel at the time of an accident are significant determinants of ship loss (Kokotos and Smirlis, 2005). The conditions of the communication equipment and personal safety equipment and maintenance operations significantly affect aviation safety (Chang and Wang, 2010). Furthermore, according to the SOLAS Convention a ship must set up rescue equipment for emergencies, such as fire pumps, generators, air compressor and lifeboats etc., and these devices must be available at any time.

2.3.3. *Ship management.* Ship management is defined as the implementation of the safety management on board a ship. Lu and Tsai (2008) examined the effects of safety cultures on container shipping safety, which include management safety practices, supervisor safety practices, safety attitude, safety training, job safety, and co-workers' safety practices. The results indicated that job safety has the most significant effect on vessel accidents, followed by management safety practices and safety training. Furthermore, relevant studies also indicate that educational training has a great effect on safety in the shipping industry (Hetherington et al., 2006). Operational procedures, regulations and performance assessment of training are significant determinants of occupational accidents (Fabiano et al., 2010).

2.3.4. *Organisation management.* Organisation management is defined as the safety policy and management system of a shipping company. Relevant studies revealed the attitude of the carrier is the most significant factor on safety management, followed by crew work stress and crew safety knowledge (Havold, 2005). The carrier's safety policy and safety management have significantly positive effects on crew safety behaviours in container shipping (Lu and Yang, 2010). Organisational culture may influence the performance of safety management in aircraft maintenance technicians (Chang and Wang, 2010). An unfair reward system would result in staff dissatisfaction, leading to decreased work and safety performance (Chang and Wang, 2010).

3. RESESARCH METHOD. In this paper, the Risk Factors (RFs) for operational safety of oil tankers are first identified. A fuzzy AHP approach is then employed to weight those RFs, including both weights of consequence and likelihood. Based on those weights, a revised risk matrix with a continuous scale is finally proposed to assess the risk classes of the RFs.

3.1. *Identification of risk factors.* Based on the relevant literature about safety factors of shipping operations, four constructs of risk factors (RFs) were identified as follows.

Table 1. The risk factors (RFs) and hierarchical structure for oil tankers.

Layer1: Construct	Layer 2: Risk factors (RFs)	
Human factor (HF)	HF1	Insufficient safety knowledge.
	HF2	Insufficient self-regulation.
	HF3	Insufficient work concentration.
	HF4	Overly perceived fatalism.
Machinery condition (MC)	MC1	The breakdown of the ship's machinery and equipment.
	MC2	The breakdown of the personal safety equipment.
	MC3	The breakdown of the safety monitoring systems.
	MC4	Inadequate warning marking system.
Ship management (SM)	SM1	Failing to implement SOP of work.
	SM2	Failing to implement safety drills on board ship.
	SM3	Inadequate safety training on board ship.
	SM4	Inadequate safety climate on board the ship.
Organisational management (OM)	OM1	Inadequate operational procedures for safety.
	OM2	Inadequate assessment system for safety performance.
	OM3	Inadequate reward-penalty system for safety performance.
	OM4	Inadequate staffing for tasks.

3.1.1. *Human factor (HF).* HF is defined as crew safety knowledge and work attitudes, including safety knowledge, work concentration, self-regulation and perceived fatalism etc. (Hetherington et al., 2006; Havold, 2010; Hsu, 2012; 2015).

3.1.2. *Machinery condition (MC).* MC is defined as the condition of a ship's machinery, equipment and safety facilities, including the ship's engines, personal safety equipment, safety monitoring systems, warning marking system, etc. (Gordor et al., 2005; Liu et al., 2006; Chang and Wang, 2010; Hsu, 2012).

3.1.3. *Ship management (SM).* SM is defined as the implementation of the safety system and the crew perceived safety climate on board the ship, including the implementation of safety procedures, safety drills, assessment of safety training, safety culture, etc. (Hetherington et al., 2006; Lu and Tsai, 2008; Fabiano et al., 2010).

3.1.4. *Organisational management (OM).* OM is defined as the safety policy and management system of ship carriers, including safety operational procedures, punishment systems, staffing of tasks, and the performance assessment of work safety (Havold, 2005; Chang and Wang, 2010; Lu and Yang, 2010).

Based on the above definitions, a two-layer hierarchical structure of RFs for oil tanker operations was first constructed. To improve the practical validity of the RFs, two practical experts were then invited to revise those RFs and check if any important RFs were missed. Further, they also checked the independences between those RFs. The two experts were a shipmaster and a chief engineer. Both came from the CPC oil tank fleet and have over 20 years of experience on board ship. After several rounds of discussion and revision, including combining two items and adding one new item, the final hierarchical structure of the RFs, shown in Table 1, contains four constructs of RFs for the first layer and 16 RFs for the second layer.

3.2. *Questionnaire design.* In this paper, an AHP questionnaire with a nine-point rating scale was designed to measure the subject's perceived likelihood and consequence on each RF respectively. Based on the hierarchical structure of RFs in Table 1, an AHP survey with five criteria and 16 sub-criteria was created. To validate the scale, the survey was then

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Table 2. Profiles of the respondents.

Characteristics	Range	Number	Percentage (%)
Job title	Shipmaster	6	25·00
	Chief officer	6	25·00
	Chief engineer	6	25·00
	Second engineer	6	25·00
Age (years)	Under 40	6	8·34
	41–50	4	20·83
	51–60	8	33·33
	Above 60	6	25·00
Educational level	University	7	29·17
	College	8	33·33
	High school	9	37·50
Seniority	5–10	5	20·83
	11–15	3	12·50
	16–20	4	16·67
	Above 20	12	50·00
Ship size (DWTs)	Under 1,0000	4	16·67
	1,0000–3,0000	8	33·33
	30,000-60,000	12	50·00

pre-tested by the previous two experts who checked the survey. Based on the results of pre-tests, some statements in the survey were revised.

3.3. *Research sample.* Since this paper employs the oil tanker fleet of CPC (Chinese Petroleum Corporation) as an empirical study to validate the proposed model, the top-four crews working in CPC's oil tanker fleet were surveyed, including shipmasters, chief officers, chief and second engineers. To improve the survey validity, an assistant was assigned to help the subjects to fill out the questionnaire. Currently, CPC's fleet has seven oil tankers with a total of 28 top-four crews, in which six vessels with 24 top-four crews were surveyed in this study. For each of the surveyed sample, a Consistency Index (CI) was first employed to test its consistency. The results indicated four samples with CI > 0.1 were highly inconsistent (Saaty, 1980). Thus, those four respondents were asked to revise their survey. This step was performed repeatedly until all surveys were consistent. The profiles of the validated 24 respondents' features are shown in Table 2. The result shows that all subjects have at least five years of work experience (with 75% of subjects over ten years) in their company. Note, the remarkable qualifications of the respondents endorse the reliability of the survey findings.

3.4. *The weights of risk factors.* In this paper, 24 pairwise comparison matrices are obtained for each comparison of RFs in each layer. In the past, most relevant studies employed arithmetic mean or geometric mean to present multiple subjects' opinions. However, those two means are sensitive to extreme values. Thus, a fuzzy number is considered to integrate the 24 subjects' perceptions in this paper. Firstly, the geometric mean was employed to represent the consensus of respondents (Saaty, 1980; Buckley, 1985). A triangular fuzzy number characterised with minimum, geometric mean and maximum of the measuring scores was then used to integrate the 24 pairwise comparison matrices into a fuzzy positive reciprocal matrix. Then, based on this matrix, a fuzzy AHP approach was employed to weight the RFs for both of the measurements of the respondents' perceived "likelihood" and "consequence".

3.4.1. *The fuzzy positive reciprocal matrix.* Suppose $\tilde{A} = [\tilde{a}_{ij}]_{n\times n}$ is a fuzzy positive reciprocal matrix where $\tilde{a}_{ij} = [l_{ij}, m_{ij}, u_{ij}]$ is a triangular fuzzy number with

$$[l_{ij}, m_{ij}, u_{ij}] = \begin{cases} [1, 1, 1], & \text{if } i = j; \\ [1/u_{ji}, 1/m_{ji}, 1/l_{ji}] & \text{if } i \neq j. \end{cases}$$

For ease of exposition, let $A^{(k)} = [a_{ij}^{(k)}]_{n\times n}$ denote the pairwise comparison matrix with n RFs for the kth subject. Then, according to the above integration procedure, the 24 pairwise comparison matrices $A^{(k)}$, $k = 1, 2, \ldots, 24$, can be integrated into the following fuzzy positive reciprocal matrix:

$$\tilde{A} = \left[\tilde{a}_{ij}\right]_{n\times n} \tag{1}$$

where $\tilde{a}_{ij} = \left[\min_{1\leq k\leq 30}\left\{a_{ij}^{(k)}\right\}, \left(\Pi_{k=1}^{30} a_{ij}^{(k)}\right)^{1/30}, \max_{1\leq k\leq 30}\left\{a_{ij}^{(k)}\right\}\right]$ is a triangular fuzzy number, $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, n$. According to the arithmetic operations of fuzzy numbers (Kaufinami and Gupta (1991)), the fuzzy positive reciprocal matrix $\tilde{A} = [\tilde{a}_{ij}]_{n\times n}$ can be expressed as follows:

$$\tilde{a}_{ij} = \begin{cases} [1, 1, 1], & \text{if } i = j; \\ (\tilde{a}_{ji})^{-1}, & \text{if } i \neq j. \end{cases}$$

3.4.2. *The consistency tests.* Before calculating the weights of the RFs via the matrix $\tilde{A}$, an immediate problem is how to test the consistency of such a fuzzy positive reciprocal matrix. Buckley (1985) conducted the consistency test for a fuzzy positive reciprocal matrix whose entries are trapezoid fuzzy numbers. He used the geometric means to defuzzify the fuzzy numbers and thus convert the fuzzy positive reciprocal matrix into a crisp matrix. Then the consistency test can be undertaken for the crisp matrix by the same method in an AHP. In this paper, the method of Buckley (1985) is used to defuzzify the $\tilde{A}$. Consequently, the fuzzy entries $\tilde{a}_{ij} = [l_{ij}, m_{ij}, u_{ij}]$ in the $\tilde{A}$ can be defuzzified as:

$$a_{ij} = (l_{ij} \cdot m_{ij} \cdot m_{ij} \cdot u_{ij})^{1/4}, \quad i = 1, 2, \ldots, n, \; j = 1, 2, \ldots, n \tag{2}$$

Generally, the following Consistency Index (CI) and Consistency Ratio (CR) are two indices used to test the consistency of a positive reciprocal matrix (Saaty, 1980):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

and

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{4}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the positive reciprocal matrix and n is the number of sub-criteria of the matrix. RI represents a Randomized Index shown in Table 3 (Sahin and Senol, 2015). Saaty (1980) suggested that the CR ≤ 0.1 is an acceptable range.

The consistency tests of the positive reciprocal matrices for likelihood measurements are shown in the second row of Table 4. The third row in Table 4 shows the results of the consistency tests for consequence measurements. Since all the CI and CR indices in Table 4 are less than 0.1, all the positive reciprocal matrices in the sample data are consistent.

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Table 3. The Randomized Index (RI).

n	3	4	5	6	7	8	9	10	11	12
R.I.	0·525	0·882	1·115	1·252	1·341	1·404	1·452	1·484	1·513	1·535

Table 4. The results of the consistency tests.

Measurements	Constructs	CI	RI	CR
Likelihood	Layer 1	0·0051	0·882	0·006
	Layer2: HF	0·0062	0·882	0·007
	Layer2: MC	0·0124	0·882	0·014
	Layer2: SM	0·0146	0·525	0·028
	Layer2: OM	0·0218	0·525	0·042
Consequence	Layer 1	0·0212	0·882	0·024
	Layer2: HF	0·0056	0·882	0·006
	Layer2: MC	0·0122	0·882	0·014
	Layer2: SM	0·0219	0·525	0·042
	Layer2: OM	0·0120	0·525	0·023

Table 5. The likelihood weights of risk factors (RFs).

Layer 1 RFs	The global weights of Layer 1 RFs (%)	Layer 2 RFs	The local weights of Layer 2 RFs (%)	The global weights of Layer 2 RFs (%)
HF	20·35	HF1	12·00	2·44
		HF2	25·59	5·21
		HF3	13·59	2·77
		HF4	48·82	**9·93**
MC	22·87	MC1	19·20	4·39
		MC2	25·59	5·85
		MC3	27·68	6·33
		MC4	27·53	6·30
SM	30·66	SM1	18·54	5·68
		SM2	19·09	5·85
		SM3	36·06	**11·06**
		SM4	26·31	8·07
OM	26·12	OM1	19·09	4·99
		OM2	21·81	5·70
		OM3	34·90	**9·12**
		OM4	24·20	6·32

Note: The boldfaced numbers present the RFs with higher weights.

3.4.3. *The weights of RFs.* In this paper, we adopted the NGMR (Normalisation of the Geometric Mean of the Rows) method (Saaty, 1980) to determine the local weights of RFs in $\tilde{A}$, which is elaborated in the Appendix. Further, the global weights of the RFs can then be found by multiplying the low level of local weights of the RFs by their corresponding high level of global weights. The results are shown in Table 5 (for likelihood measurement) and Table 6 (for frequency measurement). For example, in Table 5, the local weight of HF1 is 20.25%, and its corresponding high level of global weight (i.e the HF construct's weight)

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Table 6. The consequence weights of risk factors (RFs).

Layer 1 RFs	The global weights of Layer 1 RFs (%)	Layer 2 RFs	The local weights of Layer 2 RFs (%)	The global weights of Layer 2 RFs (%)
HF	33·38	HF1	36·34	**12·13**
		HF2	26·01	**8·68**
		HF3	29·92	**9·99**
		HF4	7·73	2·58
MC	22·19	MC1	34·47	7·65
		MC2	24·38	5·41
		MC3	22·73	5·04
		MC4	18·42	4·09
SM	18·03	SM1	26·99	4·87
		SM2	42·21	7·61
		SM3	14·99	2·70
		SM4	15·81	2·85
OM	26·40	OM1	25·63	6·77
		OM2	28·56	7·54
		OM3	17·17	4·53
		OM4	28·63	7·56

Note: The boldfaced numbers present the RFs with higher weights.

is 12.00%. Then, the global weight of HF1 should be: 20.25% × 12.00% = 2.44%, shown in the last field of Table 5.

3.5. *The revised risk matrix.* Obviously, a Risk Factor (RF) with higher likelihood weight and consequence weight should be a RF with higher risk. Based on this concept, a Risk Index (RI) is thus constructed by the product of consequence weight and likelihood weight (Cox, 2008; Levine, 2012; Montewka et al., 2014). Let ω_i^L and ω_i^F be the consequence weight and likelihood weight of *i*th RF respectively. Then, the Risk Index of *i*th RF is defined as

$$RI_i = \omega_i^L \times \omega_i^F, \quad i = 1, 2, \ldots, n \tag{5}$$

Finally, the RI can be normalised as:

$$RI_i = \frac{\omega_i^L \times \omega_i^F}{\sum_{i=1}^{n}(\omega_i^L \times \omega_i^F)} \times 100\%, \quad i = 1, 2, \ldots, n \tag{6}$$

Based on Equation (5) and the RFs' likelihood and consequence weights in Table 5 and Table 6, the RIs (Risk Indices) for each RF can be found in the last field of Table 7. The result indicates the RF with the highest risk is OM4 (8.82%), followed by HF2 (8.34%) and SM2 (8.22%).

Based on the Risk Indices (RIs), a revised risk matrix with continuous curves is constructed to classify the RFs in this paper. The matrix is shown in Figure 2, in which the consequence weight is depicted on the x-axis and the likelihood weight on the y-axis. Based on Equation (6), three decreasing curves (C_1, C_2, and C_3) with different RI means are created to divide the matrix into four quadrants which are named as E (Extreme risk), H (High risk), M (Medium risk) and L (Low risk). The first curve C_1 with RI mean = 6.25% are obtained by averaging all the 16 RFs' RIs. This divides all the RIs into two groups. Group one contains five RFs: OM4, HF2, SM2, OM2 and OM3, by which the second curve C_2

Table 7. The classification of risk factors (RFs).

RFs	Likelihood weights (%)	Consequence weights (%)	Risk Index (%)	Risk class
OM4	6·32	7·56	**8·82**	**E**
HF2	5·21	**8·68**	**8·34**	
SM2	5·85	7·61	**8·22**	
OM2	5·70	7·54	7·93	**H**
OM3	**9·12**	4·53	7·63	
OM1	4·99	6·77	6·23	**M**
MC1	4·39	7·65	6·20	
MC3	6·33	5·04	5·89	
MC2	5·85	5·41	5·84	
SM3	**11·06**	2·70	5·51	
HF1	2·44	**12·13**	5·47	
SM1	5·68	4·87	5·10	**L**
HF3	2·77	**9·99**	5·10	
MC4	6·30	4·09	4·75	
HF4	**9·93**	2·58	4·73	
SM4	8·07	2·85	4·24	

Note: The boldfaced numbers present the RFs with higher weights.

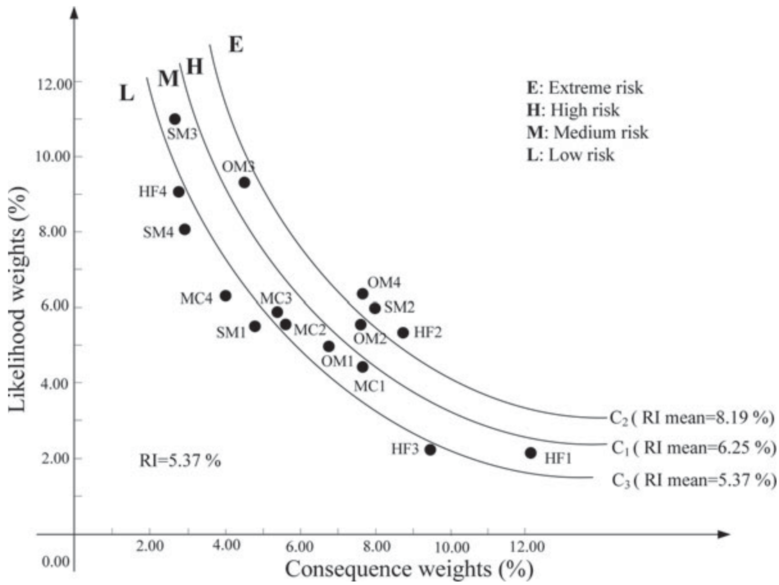

Figure 2. The revised risk matrix.

with RI mean = 8.19% is found by averaging their RIs. Likewise, averaging the rest of 11 RFs' RIs in the other group, we have the third curve C_3 with RI mean = 5.37%. The results, shown in Figure 2, indicate three RFs (OM4, HF2 and SM2) are classified as: E, two RFs (OM2 and OM3) as: H, six RFs as: M, and five RFs as: L. In practice, for the RFs in the first two classes E and H, CPC's managers should pay more attention to improving their safety.

4. DISCUSSION.

4.1. *The result of revised risk matrix.* In the relevant literature the traditional risk matrix with a discrete scale measurement may limit its applications. Thus, some revised risk matrices with continuous scale were developed to improve on the limitations. However, in those studies, respondents need to score each RF directly based on their subjective perceptions. In practice, it may be difficult for respondents to score a RF precisely in such a directly scoring measurement. Relatively comparable scoring could be more objective for evaluating the RF's consequence and likelihood degrees. For example, it could be easier for respondents to compare which RF is more likely to occur in two RFs rather than to score each of the two RF's likelihoods directly. In this paper, based on a fuzzy AHP approach a relatively comparable scoring is proposed to weight the RFs, by which a revised risk matrix with continuous curves is then yielded to classify the RFs. Compared to the previous studies, the proposed risk matrix could increase the measurement validity of the respondents, leading to improved assessment performance of the risk matrix.

4.2. *The result of empirical study.* The empirical result shows that three RFs are classified as extreme risk: OM4 (Inadequate staffing for tasks), HF2 (Insufficient self-regulation) and SM2 (Failing to implement safety drills on board ship); and two RFs are classified as high risk: OM2 (Inadequate assessment system for safety performance) and OM3 (Inadequate reward-penalty system for safety performance). This result indicates Organisation management (OM), which contains three E-H risk classes of RFs (OM2, OM3 and OM4), is the RF construct with the highest risk. Based on the results, this paper further conducted post-interviews with the previous two experts who checked and pre-tested the survey, and proposes suggestions for improving the safety of oil tanker operations as follows.

4.2.1. *Improving organisational management.* The result indicates Organisational Management (OM) with three E-H class of RFs is the highest risk construct, including staffing of tasks (OM4), assessment system (OM2) and reward-penalty system (OM3) for safety performance. For OM4, this paper suggests CPC should perform a work study to measure crews' work contents regularly, including workload and work balance. In practice, overload is one of the main determinants of crews' fatigue, leading to increased work accidents. For OM2, this paper suggests the assessment system for safety performance should be practical and realistic, and the system should be revised regularly. As for OM3, the reward-penalty for crews' safety performance should be significant. In practice, an adequate reward-penalty system could effectively discipline crews' safety behaviour.

4.2.2. *Improving crew literacy.* Practically, for improving HF2 (crew self-regulation), carrier managers may focus on enhancing crew literacy. The post-interview indicates that crew motivation to work on board ships is weak in Taiwan, leading to ship carriers needing to employ more foreign crews. Due to differences in language, culture and lifestyle, those foreign crews have poorer self-regulation. This may result in decreasing their work and safety performance, meaning HF2 has a higher improvement priority. This paper suggests ship carriers may make a policy to cooperate with maritime schools to train students for recruit crews, by which ship carriers may decrease the number of foreign employees, and improve crew literacy.

4.2.3. *Improving the performance of training.* For improving SM2 (safety drills on board ship), carrier managers may construct a complete training system. For ships' crews, there are two types of training: license training and shipboard drills. The former, which is held at safety organisations on land, may increase the crew's advanced knowledge of safety, such as tanker accident features, identification, prevention, rescue etc, while the latter (drills) is held on board the ship. For example, each crew member needs to participate in an abandon ship drill and a fire drill on board each month. However, those drills must be implemented regularly and in a realistic manner, so they do not become a mere formality.

5. CONCLUSION. This article is aimed at the risk assessment of operational safety for oil tankers. In this paper, sixteen Risk Factors (RFs) were constructed for oil tanker operations. The result can provide a reference for relevant studies on oil tanker safety. Further, based on a fuzzy AHP approach, a revised risk matrix with a continuous scale was proposed to assess the RFs' risk classes. The revised risk matrix may improve the traditional risk matrix and provide a theoretical reference for methodological researches in risk assessment of accident.

For validating the practical application of the proposed model, CPC's oil tanker fleet in Taiwan was empirically investigated. The result identifies five Extreme (E) or High (H) Risk Factors (RFs). Based on this result, some management implications and suggestions are proposed for CPC. CPC is the biggest oil tanker carrier in Taiwan. The results may provide practical information for other oil tanker operators to make policies in improving their operational safety performance. In practice, the transport of product oil tankers is used in countries with coastlines, island countries, and even landlocked countries with wide rivers. Compared to the transport of tanker trucks, it could decrease operational cost significantly. However, operational safety is vulnerable. The result may provide useful information for those countries' oil companies in operating the transports of product oil tankers

In this paper, 24 crews from CPC's oil tanker fleet in Taiwan were empirically surveyed to validate the proposed model. For enhancing the validity of the questionnaire investigation, this paper adopted an interview survey instead of a mailed survey. Thus, the validity and reliability of the findings in this paper could be endorsed. However, for better confirmation of the empirical results, more representative samples may be necessary in future research. Furthermore, due to socio-cultural differences, the results of empirical study may not be applicable to other areas. However, the research model may offer a theoretical base from which to develop a new one to fit different cultures.

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APPENDIX

Let $\tilde{A} = [\tilde{a}_{ij}]_{n\times n}$ is a fuzzy positive reciprocal matrix for n RFs, where $\tilde{a}_{ij} = [l_{ij}, m_{ij}, u_{ij}]$ is a triangular fuzzy number. Based on the arithmetic operations of fuzzy numbers (Kaufinami and Gupta, 1991), we have the geometric means ($\tilde{w}_i$) for the ith RF ($i = 1, 2, \ldots, n$):

$$\tilde{w}_i = \left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{1/n} = \left[\left(\prod_{j=1}^{n} l_{ij}\right)^{1/n}, \left(\prod_{j=1}^{n} m_{ij}\right)^{1/n}, \left(\prod_{j=1}^{n} u_{ij}\right)^{1/n}\right], i = 1, 2, \ldots, n. \quad \text{(A1)}$$

Summing up the w_i, $i = 1, 2, \ldots, n$, yields:

$$\sum_{i=1}^{n} \tilde{w}_i = \left[\sum_{i=1}^{n}\left(\prod_{j=1}^{n} l_{ij}\right)^{1/n}, \sum_{i=1}^{n}\left(\prod_{j=1}^{n} m_{ij}\right)^{1/n}, \sum_{i=1}^{n}\left(\prod_{j=1}^{n} u_{ij}\right)^{1/n}\right]. \quad \text{(A2)}$$

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Then, the fuzzy weight for the ith RFs ($i = 1, 2, \ldots, n$) can be obtained as:

$$\tilde{W}_i = \tilde{w}_i / \sum_{i=1}^{n} \tilde{w}_i = \left[\left(\frac{\left(\prod_{j=1}^{n} l_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} u_{ij} \right)^{1/n}} \right), \left(\frac{\left(\prod_{j=1}^{n} m_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} m_{ij} \right)^{1/n}} \right), \left(\frac{\left(\prod_{j=1}^{n} u_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} l_{ij} \right)^{1/n}} \right) \right], \quad i = 1, 2, \ldots, n \tag{A3}$$

Since the weight $\tilde{W}_i$ of the ith RF ($i = 1, 2, \ldots, n$) is fuzzy, this paper adopted Yager's index (1981) to defuzzify the $\tilde{W}_i$ into a crisp number W_i, $i = 1, 2, \ldots, n$. Yager's index is defined based on an area measurement. Suppose the fuzzy number $\tilde{W}_i$ with a αcut function: $W_i(\alpha) = [W_{i\alpha}^L, W_{i\alpha}^R]$, by Yager's index, the $\tilde{W}_i$ can be defuzzified as:

$$W_i = \int_0^1 \frac{1}{2} (W_{i\alpha}^L + W_{i\alpha}^R) d\alpha. \tag{A4}$$

In Equation (A3), for convenience of explanation, let $\tilde{W}_i = [l_i^W, m_i^W, u_i^W]$, where

$$[l_i^W, m_i^W, u_i^W] = \left[\left(\frac{\left(\prod_{j=1}^{n} l_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} u_{ij} \right)^{1/n}} \right), \left(\frac{\left(\prod_{j=1}^{n} m_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} m_{ij} \right)^{1/n}} \right), \left(\frac{\left(\prod_{j=1}^{n} u_{ij} \right)^{1/n}}{\sum_{i=1}^{n} \left(\prod_{j=1}^{n} l_{ij} \right)^{1/n}} \right) \right], \quad i = 1, 2, \ldots, n.$$

Based on Equation (A4), the $\tilde{W}_i$ ($i = 1, 2, \ldots, n$) can be defuzzified as (Yager, 1981):

$$W_i = (l_i^W + 2m_i^W + u_i^W)/4, \quad i = 1, 2, \ldots, n. \tag{A5}$$

Finally, normalising the W_i ($i = 1, 2.., n$), then we have the crisp weight of the ith RFs as:

$$\omega_i = W_i / \sum_{i=1}^{n} W_i, \quad i = 1, 2, \ldots, n \tag{A6}$$

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