THE JOURNAL OF NAVIGATION (2015), **68**, 162–183. © The Royal Institute of Navigation 2014
doi:10.1017/S0373463314000514

A Novel Process Model for Marine Accident Analysis by using Generic Fuzzy-AHP Algorithm

Bekir Sahin[1,2] and Yunus Emre Senol[1]

[1] (*Surmene Faculty of Marine Science, Karadeniz Technical University, Trabzon, Turkey*)
[2] (*Maritime Department, Istanbul Technical University, Istanbul, Turkey*)
(E-mail: bekirs66@gmail.com)

Marine accident analysis is a sophisticated and complex official interpretation that requires a professional and fair judgment. For accidents such as a collision, contact and other incidents in the maritime field, the judgment mechanism of the courts depends on the decision process of the field experts. Field experts define the "Fraction Defectives" (FDs) of the vessels for the intended case based on the existing evidence and navigational specifications. However, evaluation of human judgment can be limited and problematic in analysing many aspects of a case. In this paper, a pairwise comparison method is used to simplify and clarify the judgment process. We aim to assess marine accidents in a stepwise approach that is inaccurately carried out in a holistic perspective by the field experts. A real accident that occurred in the past is simulated in front of the field experts. After conducting an expert consultation, FDs are re-calculated to compare both the regular judgment and the results in our suggested Generic Fuzzy Analytical Hierarchy Process (GF-AHP) approach.

KEYWORDS

1. Algorithm. 2. Radar. 3. Navigation.

Submitted: 5 March 2014. Accepted: 18 July 2014. First published online: 15 August 2014.

1. INTRODUCTION. Accidents generally result in a serious damage, loss, death, injury or pollution, and marine accidents such as a collision, contact, grounding, fire or explosion involve large economic, political and ecological consequences. Therefore many governments investigate marine accidents by branches of their Departments of Transportation (for details see the Appendix). Courts also provide experienced field experts who are drawn from pilots, captains, naval architects or engineers. These experts mostly interpret the rules and regulations in a subjective assessment process. Ensuring justice becomes harder due to the many rules and regulations and outcomes may vary significantly.

In the conventional method, proper values of "Fraction Defectives" (FDs) are assigned as to the roles of parties (i.e. vessels) involved in the related case. In the conventional application of marine accident analysis, FDs are determined in a

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

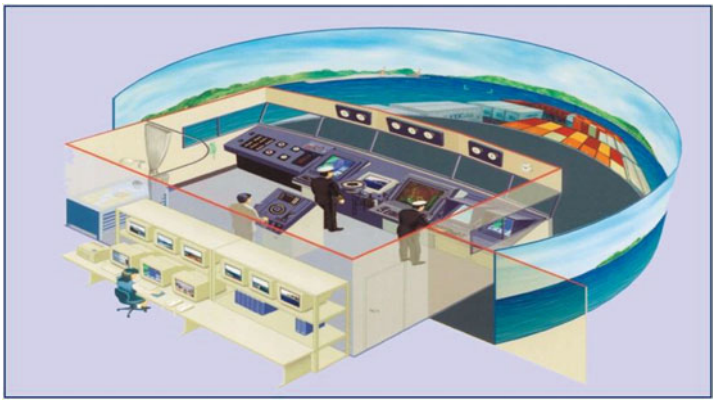


Figure 1. Illustration of the JMS full-mission ship handling simulator main bridge. (Courtesy of JMS manual).

complete assessment process and subject to bias due to the limitations of human judgment and cognitive interpretations. Thus, the losing parties often appeal to reject the decision.

This paper provides an alternative process to improve the decision making approach for marine accident analyses. A Generic Fuzzy Analytical Hierarchy Process (GF-AHP) method is proposed. This structured multi-criteria decision making method is preferred, based on its superiority derived from the decomposition of the proposed purpose, organisation of the complexity and consensus of expert consultation. Traditionally, Fraction Defective Management (FDM) is used as a method to apportion the FDs for detecting the liabilities of the involved vessels. To the best of our knowledge, FDM for collisions by using pairwise comparison has not been addressed in the literature.

The International Regulations for Preventing Collisions at Sea (COLREGS, 1972) published by the International Maritime Organization (IMO) is an international comprehensive guide for the purpose of providing safe vessel traffic at sea. In our system, each criterion (COLREG rules involved in the collision) that contributes to the causes of the collision has a percentage value. The sum of all criteria for both vessels is assumed as having a total 100% value. FD is a contributory rate obtained as a result of a GF-AHP alternative weighting process taking into consideration the criteria's weights.

The aim of this paper is to make recommendations for court experts, inspectors and accident investigators to construct a model for assigning the percentages to the FDs of each vessel's actions on a time basis. Also, this research will help the court experts to prevent the unfair FD ratings for similar incidents occurring in the future.

For this research, a historical maritime accident is selected. Contributory causes, conditions and circumstances are criticised and compared with the other assessments. Then, all these scenarios are analysed in a consideration that it will take a significant role in our navigational and operational maritime accident history. The same conditions are adapted to the same location and the same accident is simulated again with the same circumstances at the Main Bridge Simulator of the Maritime Department, Istanbul Technical University (ITU) (Figure 1).

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

Table 1. Particulars of M/V *Alpha* and M/V *Bravo*.

Particulars	M/V *Alpha*	M/V *Bravo*
Vessel Type	Bulk Carrier	Container Ship
Year Built	2011	2004
Gross Tonnage	51·285	30·154
Length Overall	228 m.	215,8 m.
Breadth Overall	37,8 m.	32·3 m.
Max. Draught	14,9 m.	12,30 m.
Service Speed	14,4 knots	18,1 knots
Cargo	82·000 mt. grain	2400 TEU
Actual Mean Draught	13,50 m.	11,20 m.

Table 2. Information of M/V *Alpha* and M/V *Bravo's* Relevant Crews.

		Age	Sea Experience	Rank Experience	English Communication Skill
M/V *Alpha*	Master	35	10 years	3 years	N/A
	3rd Officer	27	3 years	3 years	Poor
	Able Seaman	37	13 years	8 years	None
M/V *Bravo*	Master	43	18 years	10 years	N/A
	3rd Officer	29	5 years	5 years	Good
	Able Seaman	51	29 years	24 years	Poor

2. COLLISION ASSIGNMENTS. First of all, we prefer to conceal the names of the vessels for ethical reasons and the possibility of affecting court decisions. However, the remainder of the data of the vessels implemented for the collision of our imaginary vessels is based on a real incident. The particulars of the imaginary vessels (M/V *Alpha* and M/V *Bravo*) are given in Table 1.

Information of the relevant crews for both vessels is given in the Table 2.

Recorded conditions on the day of the accident were:

- Height of Tide: 0·3 m.
- Tidal Stream: WNW 0·2 knots
- Wind Speed – 10 knots
- Wind Direction – SE
- Sea – S/2 m.
- Visibility – 10 nm.

On 7 July 2013 at 22:19:45 hours, M/V *Alpha* and M/V *Bravo* collided in the eastern approaches of the Singapore Strait, 6·5 nm NE bearing of Horsburg Lighthouse. Details of the accident in terms of both sides are given below.

2.1. *Bridge of M/V Alpha.* At approximately 21:25 M/V *Alpha* passed abeam Horsburg Lighthouse, and maintained heading 048° (T) at a speed of 9·8 knots. The officer of the watch was the 3rd Officer whose English was poor. An able seaman was also present as a lookout. Radar was adjusted to 6 nm range, head up, relative motion, off centre and 3 min trails function was activated. At 22:00, 20 minutes prior to collision, the officer adjusted the radar range to 12 nm. Positions of the vessels are shown in Figure 2.

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

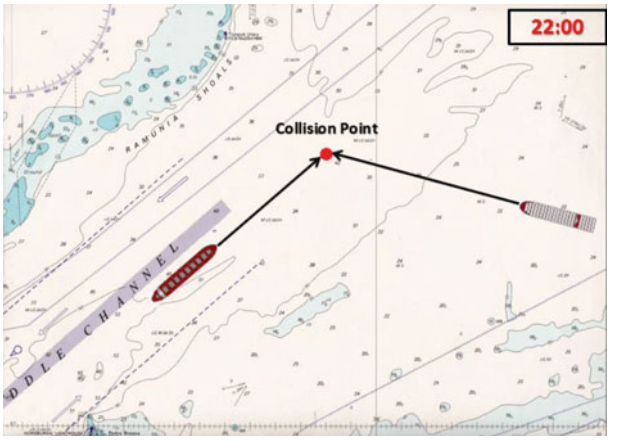


Figure 2. Illustration of the Vessels on British Admiralty Chart (BA 3831) 22:00.

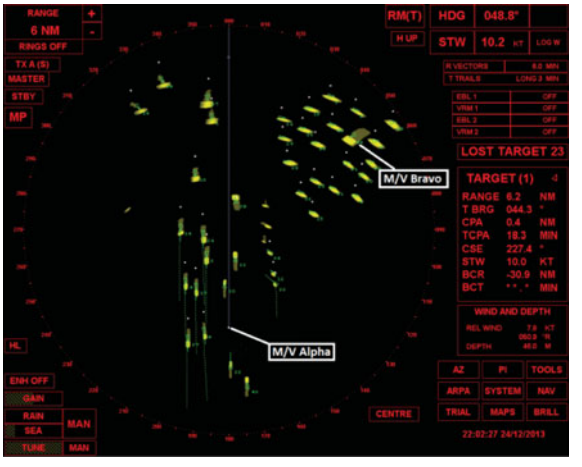


Figure 3. Simulated Radar Screenshot on M/V *Alpha*, 22:02.

M/V *Bravo* was a vessel approaching from the starboard bow on a collision course and was visible on the radar screen with clear trail as seen in Figure 3. After a while, the officer adjusted the range back to 6 nm and M/V *Bravo* was still visible on the radar screen.

As the vessel approached the eastbound Traffic Separation Scheme (TSS) lane, there was heavy vessel traffic; transiting vessels in both lanes of the TSS, fishing vessels on the starboard side of M/V *Alpha*, some of which were sailing and some not, and anchored vessels on the starboard bow which were disturbing the view with their deck lights on. Therefore the officer could not detect M/V *Bravo* visually as it transited between anchored vessels.

The simulated radar screenshot is compared with the real radar records (Figure 4) derived from the Voyage Data Recorder (VDR), which records all critical data related to the voyage. As is seen from Figures 3 and 4, both these radar screenshots indicate the same moment. However, there is one difference between these images concerning the radar scaling. Since the original radar is adjusted to 12 nm, as mentioned in the

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

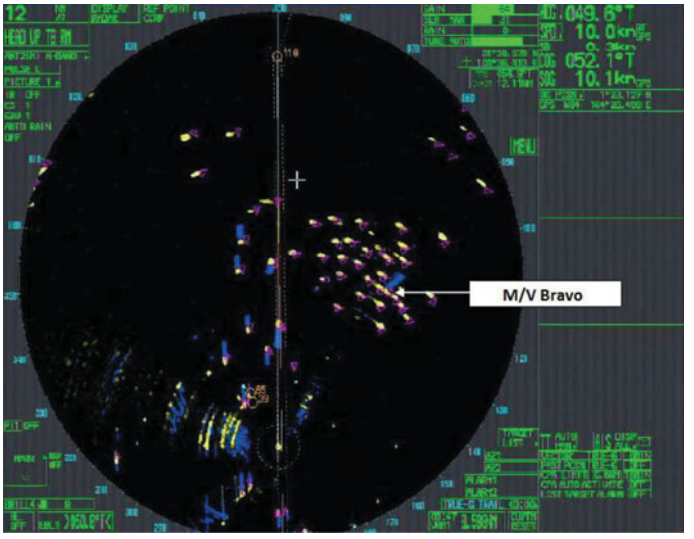


Figure 4. Real Radar Screenshot from M/V *Alpha*, 22:02.

narrative of the event, our simulated image indicates that it is adjusted to 6 nm. In that respect, the vessels at a distance of more than 6 nm, seen on the real radar screen, are not visible on our simulated radar image.

Though it is a very tough task to create such a scenario to make the real accident happen by using simulators, we simulated the collision as closely as possible. The similarities between two images are clearly seen in Figure 4.

At 22:08, 12 minutes prior to collision, at a distance of 4·5 nm from M/V *Bravo*, the officer plotted her on the radar, and identified the ship with the Automatic Identification System (AIS). He noticed the unchanging bearing and 0·0 nm Closest Point of Approach (CPA) value on radar screen when Time to Closest Point of Approach (TCPA) was 12·5 minutes (Figure 5). Though M/V *Alpha* was the give-way vessel and M/V *Bravo* was the stand-on vessel according to International Regulations for Preventing Collisions at Sea (COLREGS, 1972), the officer hoped M/V *Bravo* would make an evasive manoeuver, as M/V *Alpha* could not manoeuver due to congested traffic. However, he did not make any communication with the other vessel and M/V *Alpha* maintained its course and speed.

At 22:15, 5 minutes prior to the collision, when the distance between the vessels was 2 nm, the officer of M/V *Alpha* called the M/V *Bravo* on Very High Frequency (VHF) Radio channel 16 without receiving any response (Figure 6).

At 22:16, 4 minutes prior to the collision, the officer made another call, which was responded to by the M/V *Bravo*. They agreed to maintain communication on VHF channel 15. Officers could hear each other clearly, but the communication was interrupted by other ships' communication. After a few seconds, a sound was heard on VHF "Increase your speed, I will pass clear of you." The officer of M/V *Alpha* tried to communicate with M/V *Bravo* without receiving any response for 3 minutes, while both vessels were maintaining course and speed. At 22:20:09, 30 seconds prior to the collision, the officer of M/V *Alpha* started a hard port turn in order to prevent the collision.

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

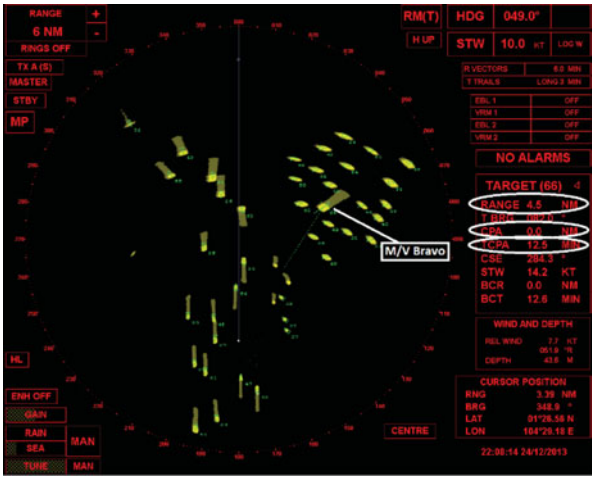


Figure 5. Simulated Radar Screenshot of M/V Alpha 22:08 (CPA: 0·0 nm., TCPA: 12·5 min., Range: 4·5 nm).

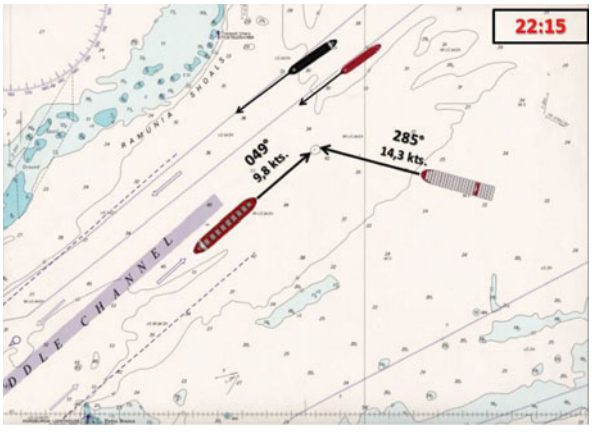


Figure 6. Illustration of the Vessels Chart BA3831, 22:15.

2.2. *Bridge of M/V Bravo*. M/V Bravo was proceeding towards the eastern approaches to the Singapore Strait from the east at a speed of 14·5 knots. At 20:00, the 3rd Officer took over the bridge watch, and there was an able seaman as a lookout. Radar was adjusted to the 12 nm range, north up, relative motion, off centre and the 3 min trails function was activated. At 20:15 the master came to the bridge to check traffic and prepare night orders. After 10 minutes, the master told the officer to call him at a certain point near the TSS and in case of any heavy traffic and then the master left the bridge. At 20:35 course was altered from 311° (T) to 284° (T). At approximately 21:20 the officer noticed many targets on the radar screen: anchored vessels ahead and some fishing vessels on the starboard bow. He decided to pass through the anchored vessels by adjusting CPA to 4 cables and radar range to 6 nm. At 21:40, the officer noticed that two ships were proceeding to the TSS from northeast, on his starboard bow, which were on a probable collision course. He was fully

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

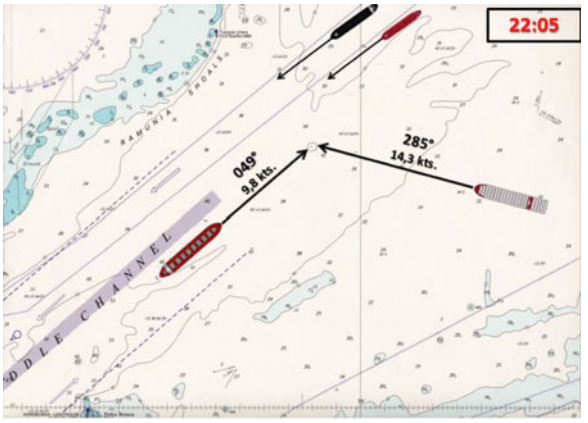


Figure 7. Illustration of the Vessels on Chart BA 3831. 22:05.

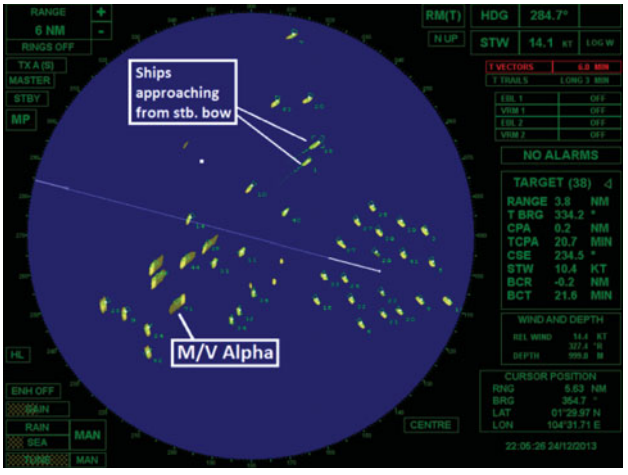


Figure 8. Simulated Radar Screenshot of M/V *Bravo*, 22:05 (the officer plotted the ships approaching from stbd bow and M/V *Alpha* was visible on the screen).

concentrating on these vessels and a planned hard turn to port after them. The officer did not notice the approaching vessels from the port bow and neither did the able seaman who was on duty as a lookout.

At 22:05, 15 minutes prior to collision, M/V *Alpha* was visible on radar screen at a distance of 6 nm (Figures 7 and 8).

Both vessels maintained their courses and speeds. At 22:08, 12 minutes prior to collision, though the distance between the M/V *Alpha* and M/V *Bravo* was decreasing dangerously, the officer did not notice the M/V *Alpha*, as he was concentrating on the vessels approaching from the starboard bow (Figure 9).

At 22:14, 6 minutes prior to collision, the normal situation on the bridge was changed suddenly, when the officer noticed the green side light on his port bow at a distance of 2 nm. (Figure 10). Following this, the officer plotted the other ship on radar, and plotted his own position on the Chart. M/V *Alpha* called M/V *Bravo* on

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

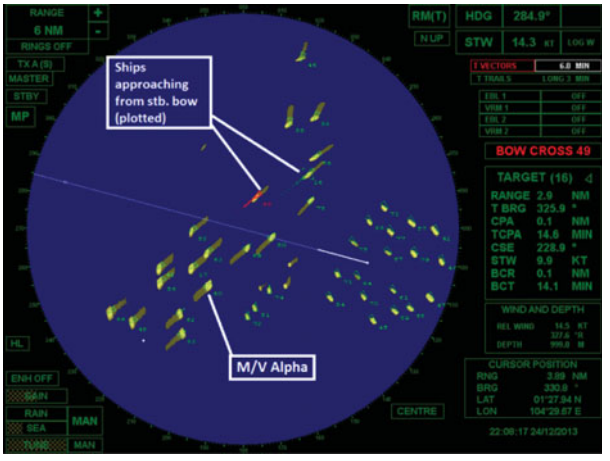


Figure 9. Simulated Radar Screenshot of M/V *Bravo*, 22:08 (The officer is still fully concentrating on ships approaching from starboard bow).

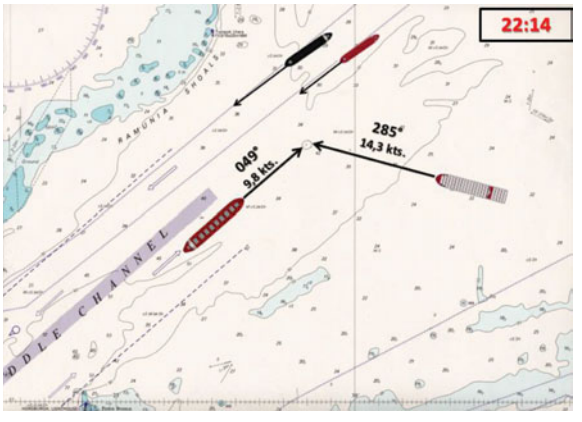


Figure 10. Illustration of the Vessels on Chart BA 3831, 22:14.

VHF Ch. 16. He responded to the call, and agreed to communicate on channel 15. Communication was not effective.

At 22:17, 3 minutes prior to collision, M/V *Alpha* requested M/V *Bravo* to increase speed to pass clear of M/V *Alpha* which made the officer of M/V *Bravo* confused, and he could not understand the intentions. He knew it was quite impossible to increase the speed of the ship in time, so he did not respond and assumed the request was not relevant for him, as the other vessels were very close to him. At 22:18, 2 minutes prior to collision, he decided to call the master while he was maintaining course and speed. At 22:19:47, 1 minute prior to collision, he made a hard turn to starboard manually to prevent the collision. Figure 11 indicates the moment of collision.

3. METHODOLOGY

3.1. *Fuzzy sets and triangular fuzzy numbers.* Linguistic variables are expressed as fuzzy words instead of numbers in a type of artificial language. For instance,

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

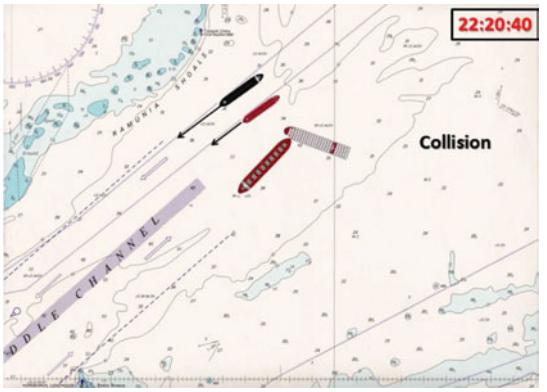


Figure 11. The Moment of Collision on Chart BA3831, 22:20:40.

weather condition is such a variable, and expressed as cold, very cold, hot or very hot (Bellman and Zadeh, 1977).

A linguistic variable is approximate because of its character of being too complex or unclear for description in quantitative terms. Humanistic systems commonly use linguistic variables such as human supported decision systems, law, economy, medical realms, artificial intelligence, pattern recognitions and related areas (Zadeh, 1975).

Zadeh firstly developed and introduced Fuzzy sets (Zadeh, 1965). A triangular fuzzy number is a convex and normalized fuzzy set $\tilde{A}$ and $\mu_{\tilde{A}}$ (x) is the continuous linear function which is membership function of $\tilde{A}$.

$\tilde{A}$ is the subset of X for all x $\in X$, which is assumed a universe of discourse. $\mu_{\tilde{A}}$ (x) $\in$ [0,1] is the membership function of $\tilde{A}$ and represents the membership of x to $\tilde{A}$.

A triangular fuzzy number $\tilde{A} = (l, m, u)$ is basically,

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < l, \\ (x-l)/(m-l), & l \leqslant x < m, \\ 1, & x = m, \\ (u-x)/(u-m), & m < x \leqslant u, \\ 0, & u < x. \end{cases} \tag{1}$$

where l and u are the upper value and lower value, which are bounds of fuzzy number $\tilde{A}$ and m is the midpoint. A triangular fuzzy number (TFN) is shown in Figure 12.

Arithmetic operations between TFN and crisp numbers are defined by Zadeh (1965) which are given below:

Two positive triangular fuzzy numbers l_1, m_1, u_1 and l_2, m_2, u_2 then:

$$(l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$$
$$(l_1, m_1, u_1).(l_2, m_2, u_2) = (l_1.l_2, m_1.m_2, u_1.u_2)$$
$$(l_1, m_1, u_1)^{-1} = (1/u_1, 1/m_1, 1/l_1)$$
$$(l_1, m_1, u_1).k = (l_1.k, m_1.k, u_1.k)\ k \text{ is a positive number.}$$

3.2. *Fuzzy Analytical Hierarchy Process (F-AHP).* The Analytical Hierarchy Process (AHP) was firstly proposed by Saaty (1980) as a decision making tool which is

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

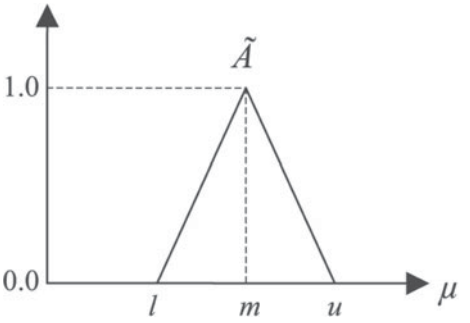


Figure 12. Triangular fuzzy number.

widely used by many researchers (Leung and Cao, 2000; Lee et al., 1999; Weck et al., 1997; Duru et al., 2012). The main purpose of AHP is to utilise expert consultation. However, the classical AHP does not reflect the human thinking style (Chang, 1996). Classical AHP uses the exact values when comparing the criteria or alternatives (Cakir and Canpolat, 2008). On the other hand, there are many criticisms based on its unbalanced scale, uncertainty and imprecision of pairwise comparisons are highly discussed in the literature. Analytical Hierarchy Process (AHP) has been evolved into the FAHP by Laarhoven and Pedrycz (1983). The FAHP overcomes the shortcomings of the fuzziness of the decision making process. FAHP is more accurate, and it is developed to handle the above shortcomings. It is accomplished by the adaptation of triangular fuzzy numbers into the pairwise comparison matrix. Then several FAHP methods are developed for various decision-making problems. Laarhoven and Pedrycz firstly proposed the FAHP by comparisons of fuzzy ratios (Laarhoven and Pedrycz, 1983). Buckley worked on trapezoidal fuzzy numbers to evaluate the alternatives with respect to the criteria (Buckley, 1985). For the pairwise comparisons Chang developed an extent analysis method for the synthetic extent values (Chang, 1996).

The steps of the extent synthesis method are:

Let $X = \{x_1, x_2 \ldots x_n\}$ as an object set and $U = \{u_1, u_2 \ldots u_n\}$ be a goal set. Each object is taken, and extent analysis is performed for each goal. Therefore, m extent analysis values for each object can be obtained.

$$M_{g_i}^1, M_{g_i}^2, \ldots, M_{g_i}^m, \quad i = 1, 2 \ldots n \tag{2}$$

where all M_g^j(j = 1,2. . .m) are the triangular fuzzy numbers.

Step 1: Regarding the ith object, the value of fuzzy synthetic extent is defined as:

$$S_i \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \tag{3}$$

Obtaining $\sum_{j=1}^{m} M_{g_i}^j$, the fuzzy addition operation of m extent analysis values for a particular matrix is performed as:

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{4}$$

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

and to obtain $\left[\sum_{i=1}^{m}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$, the fuzzy addition operation of $M_{g_i}^{j}(j=1,2\ldots m)$ values is performed as:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{5}$$

The inverse of the vector is

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right). \tag{6}$$

Step 2: The degree of possibility of $M_2=(l_2, m_2, u_2) \geqslant M_1=(l_1, m_1, u_1)$ is defined as:

$$V(M_2 \geqslant M_1) = \sup_{y \geqslant x}\left[\min(\mu_{M_1}(x), \mu_{M_2}(y))\right] \tag{7}$$

and also can be expressed as follows:

$$V(M_2 \geqslant M_1) = hgt\,(M_1 \cap M_2)$$

$$= \mu_{M_2}(d) = \begin{cases} 1, & if \quad m_2 \geqslant m_1, \\ 0, & if \quad l_1 \geqslant u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise. \end{cases} \tag{8}$$

d is the y-axis value of the highest intersection point D between μ_{M_1} and μ_{M_2}. Both V $(M_1 \geqslant M_2)$ and $V(M_2 \geqslant M_1)$ should be known for the comparison of M_1 and M_2

Step 3: The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy $M_i(i=1, 2\ldots)$ numbers can be defined by

$$\begin{aligned} &V(M \geqslant M_{1,} M_2 \ldots M_k) \\ &\quad = V[(M \geqslant M_1) and (M \geqslant M_2) and \ldots and (M \geqslant M_k)] \\ &\quad = min V(M \geqslant M_i), i = 1, 2, 3 \ldots k. \end{aligned} \tag{9}$$

Assume that for $d(A_i)=min V\ (Si \geqslant Sk) for k=1,\ 2\ldots n$; then the weight vector is given by

$$W' = (d'(A_1), d'(A_2) \ldots d'(A_n))^T \tag{10}$$

where $A_i=(i=1, 2\ldots n)$ are n elements.

Step 4: Normalization and normalized weight vectors are:

$$W = (d(A_1), d(A_2) \ldots d(A_n))^T, \tag{11}$$

where W is a non-fuzzy number.

3.3. *Design of the Application*. In this paper, a novel approach by using a F-AHP procedure named Generic Fuzzy-AHP (GF-AHP) is applied to our problem (Bulut et al., 2012). This method is an extension of the conventional method includes Centric Consistency Index (CCI) check, prioritisation of expert experience and a rank method for direct numerical inputs. The procedure

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

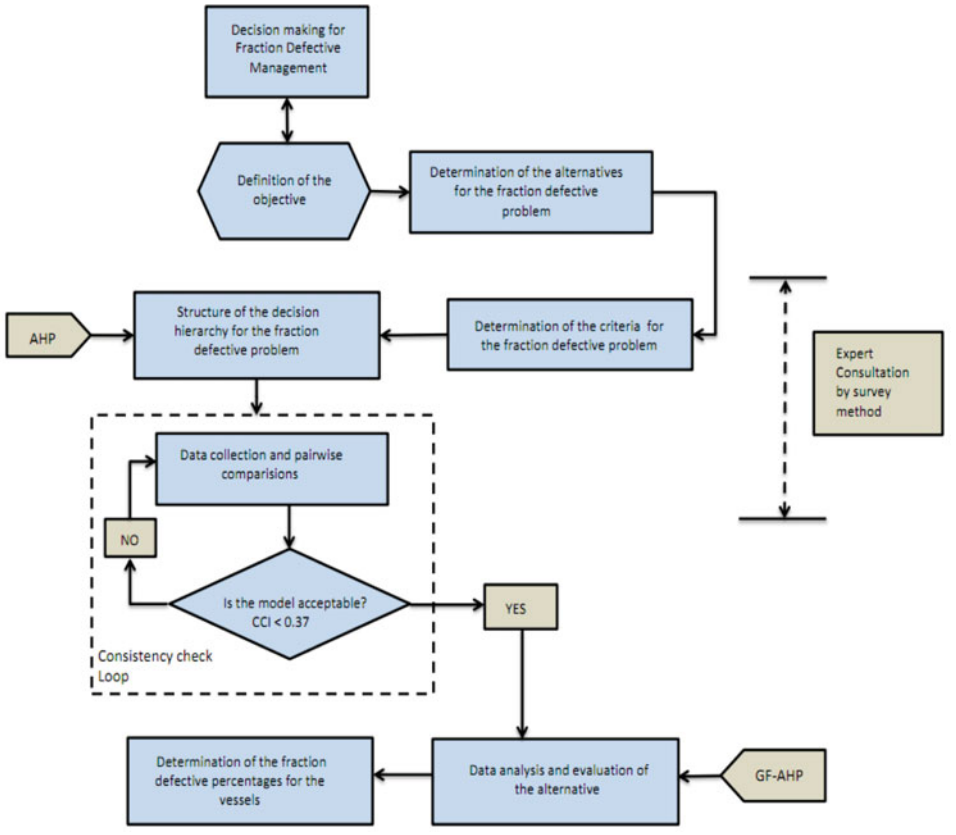


Figure 13. Procedure of GF-AHP.

of GF-AHP is shown in stepwise progress in the Figure 13. GF-AHP allows researchers to implement CCI control, expert prioritization and direct numerical inputs.

For the GF-AHP method, as an expert priority multiplier *lambda* coefficient is conducted for aggregation of individual matrices (Bulut et al., 2012). We assume $a_{ij} > 0$, $a_{ij} \times a_{ji} = 1$ and $A = (a_{ij})_{n \times n}$ is a judgment matrix. From the judgment matrix A, the prioritisation method derives a priority vector $w = (w_1, w_2 \ldots w_n)^T$, where $w_i \geqslant 0$ and $\sum_{i=1}^{n} w_i = 1$, $D = \{d_1, d_2 \ldots d_m\}$ is the set of decision makers (DM), and $\lambda = \{\lambda_1, \lambda_2 \ldots \lambda_m\}$ is the weight vector of DM, where $\lambda_k > 0$, $k = 1, 2 \ldots m$, and $\sum_{k=1}^{m} \lambda_k = 1$.

$E = \{e_1, e_2 \ldots e_m\}$ is the year of experience in their professional career for each DM, and λ_k for each DM is defined by

$$\lambda_k = \frac{e_k}{\sum_{k=1}^{m} e_k} \tag{12}$$

$A^{(k)} = (a_{ij}^{(k)})_{n \times n}$ is the judgment matrix provided by the DM d_k.

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

$w_i^{(k)}$ is the priority vector of criteria for each DM calculated as follows:

$$w_i^{(k)} = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}} \tag{13}$$

The aggregation of individual priorities is defined by

$$w_i^{(w)} = \frac{\prod_{k=1}^{m} (w_i^{(k)})^{\lambda_k}}{\sum_{i=1}^{n}\prod_{k=1}^{m} (w_i^{(k)})^{\lambda_k}} \tag{14}$$

where $w_i^{(w)}$ is the aggregated weight vector. After the aggregation process, Chang's (1996) extent synthesis methodology is applied for subsequent choice selection.

After the final consistency control, the GF-AHP procedure is completed. The consistency control and CCI for fuzzy-AHP applications is explained in the following section.

3.4. *Centric Consistency Index (CCI).* According to Saaty's approach, all matrices should be consistent (Saaty and Vargas, 1987). For consistency checking of the GF-AHP method, Bulut et al. (2012) used CCI. The Geometric Consistency Index (GCI) method formalised from the geometric mean method (RGMM) is proposed (Crawford and Williams, 1985; Aguarón and Moreno-Jiménez, 2003). For the classical AHP method, GCI measures the individual consistency of judgment matrices. Centric Consistency Index (CCI) calculates the consistency in aggregated matrices.

$$CCI(A) = \frac{2}{(n-1)(n-2)}\sum_{i<j}\left(\log\left(\frac{a_{Lij}+a_{Mij}+a_{Uij}}{3}\right) - \log\left(\frac{w_{Li}+w_{Mi}+w_{Ui}}{3}\right) + \log\left(\frac{w_{Lj}+w_{Mj}+w_{Uj}}{3}\right)\right)^2 \tag{15}$$

When $CCI(A)$ is 0, A is fully consistent. Aguarón and Moreno-Jiménez (2003) also express the thresholds ($\overline{GCI}$) as $\overline{GCI} = 0{\cdot}31$ for $n=3$; $\overline{GCI} = 0{\cdot}35$ for $n=4$ and $\overline{GCI} = 0{\cdot}37$ for $n>4$. When $CCI(A) < \overline{GCI}$ that means this matrix is sufficiently consistent.

4. ANALYSIS OF THE COLLISION.

Vessels need to follow navigation rules at sea to prevent collisions. In our real case, two vessels were involved in the accident. As a conventional approach, the COLREGs are referred to analyse marine accidents. The collision summarised in Section 2 is discussed below. Contributing factors are criticised in terms of each vessel.

4.1. *COLREG rules for the M/V Alpha.* After expert consultation, it is decided that M/V *Alpha* has violated five COLREG Rules that are detailed below. Rule 16 is unique for M/V *Alpha*.

4.1.1. *Rule 5 Lookout.* At 22:08 the officer plotted the M/V *Bravo* on the radar for the first time, 12 minutes prior to the collision when the distance between the vessels was 4·5 nm. Plotting was made by using the AIS data that are generated from

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

target ships, which could lead to not realising the critical situation. The officer should have used his own radar data for anti-collision purposes. In that respect the officer of M/V *Alpha* violated COLREG Rule 5 which is related with lookout. It mentions "Every vessel shall at all times maintain a proper lookout by sight as well as by hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision."

4.1.2. *Rule 6 Safe speed*. M/V *Alpha* was navigating with almost 10 knots speed which should be adjusted to each internal and external condition such as visibility, traffic density, stopping distance, sea condition, conditions of radar, number location and movement of vessels detected by radar etc. Therefore M/V *Alpha* should have adjusted speed in accordance with COLREG Rule 6, Safe Speed. The officer should have adjusted the speed taking into account the traffic density (Rule 6(a)(ii)), effective manoeuvre and stopping distance (Rule 6 (a)(iii)), bright lights beamed by the anchored vessels which affected the visibility at night time (Rule 6 (a)(iv)), and vessels which were very close to him, and obstructed an effective evasive manoeuvre (Rule 6(b)(v)). In that respect, the officer of M/V *Alpha* violated COLREG Rule 6.

4.1.3. *Rule 7 Risk of collision*. The officer of M/V *Alpha* noticed the risk collision and expected the other vessel to make an evasive manoeuvre due to his limited opportunities of manoeuvring. Nevertheless noticing a risk is not sufficient to prevent any collision, as the officer should have used all available means to prevent collision and make the other vessel's officer acknowledge the risk of collision (Rule 7(a)). The officer could occasionally adjust the radar range to a larger scale to obtain early warning of risk of collision (Rule 7(b)). Moreover, instead of expecting the other vessel's manoeuvre without any action on his part, the officer should have used other available equipment such as VHF to notify the risk of collision and his limited manoeuvre opportunities to the other officer. Also the officer could adjust the radar to automatic detection for any dangerous targets; even if he could not observe them. Thus the officer assumed the port side as safe, because he made an assumption which is based on scanty information about radar (Rule 7(c)). From these points of view, the officer of M/V *Alpha* violated COLREG Rule 7, risk of collision.

4.1.4. *Rule 8 Action to avoid collision*. In case of any collision situation, the most important action is to prevent the collision regardless of being give-way or stand-on vessel. Therefore, the officer of M/V *Alpha* should have tried to establish not only VHF communication earlier than 3 minutes prior to collision, but should also have slackened the speed of the ship. This means the officer did not take preventive action in ample time (Rule 8(a)). He did not take the most effective action to prevent a close-quarters situation in good time. Therefore he could not ensure passing at a safe distance (Rule 8(c)). Moreover the officer could have reduced speed to allow more time for action to avoid collision (Rule 8(e)). In that respect, the officer of M/V *Alpha* violated COLREG rule 8, as he was reluctant to take action to avoid collision due to several reasons.

4.1.5. *Rule 16 Action by give-way vessel*. In case of any situation that a vessel is directed to keep out of the way of another vessel, it should, so far as possible, take early and substantial action to keep well clear. As the officer of M/V *Alpha* did not take action as a give-way vessel, he violated COLREG rule 16, action by give-way vessel. A time chart of the actions taken by M/V *Alpha* is given in Table 3.

4.2. *COLREG rules for M/V Bravo*. Field experts confirmed that M/V *Bravo* has violated five COLREG Rules. Rule 17 is unique for M/V *Bravo*.

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

Table 3. Actions taken by the vessels.

Time	M/V *Alpha*	M/V *Bravo*
22:00	• Proceed to 048° (T) at a speed of 9·8 knots	• Proceed to 284° (T) at a speed of 14·5 knots
22:05	• Notice the ship on radar screen, but not visually • Maintain course and speed	• Pass through anchored vessels • Concentrated vessels, approaching from starboard bow • Maintain course and speed
22:08	• Plot the target on radar	• Maintain course and speed
22:14	• Maintain course and speed	• Notice green side light of other vessel • Maintain course and speed
22:15	• Call the other vessel on VHF • Maintain course and speed	• Response the VHF call • Maintain course and speed
22:19	• Make a hard port turn	• Make a hard starboard turn
22:20	• Collision	• Collision

4.1.1. *Rule 5 Lookout*. During navigation, the officer of the watch should at all times carry out a proper lookout. Proper lookout not only means observing the stand-on vessels, but also observing give-way vessels. Though M/V *Bravo* was the stand-on vessel according to COLREG, the officer of M/V *Bravo* should not have observed only the stand-on vessels for him. Also he did not notice the vessels approaching from the port bow on the radar screen. When the officer of M/V *Alpha* called the M/V *Bravo*, the astonishment of the officer of M/V Bravo is an obvious indicator that he did not notice the M/V *Alpha* earlier. Observations on the bridge should be maintained to avoid collision. In that respect, the officer of M/V *Bravo* violated COLREG Rule 5, lookout.

4.1.2. *Rule 6 Safe speed*. M/V *Bravo* was navigating at almost 14.5 knots speed that may be considered excessive speed in such congested areas, thus a circular related to safety of navigation in the Singapore Strait and published by Maritime and Port Authority of Singapore Strait, restricts the speed of vessels to 12 knots within the Strait. Though M/V *Bravo* was not inside the Strait, she was exposed to the congested traffic that perhaps should have prompted a lower speed. For the purpose of adjusting speed, the officer of M/V *Bravo* should have taken into account the CPA value of anchored vessels (Rule 6(a)(ii)), effective manoeuvre and stopping distance (Rule 6 (a)(iii)), bright lights of the anchored vessels (Rule 6(a)(iv)) and vessels which were very close to him and obstructing an effective evasive manoeuvre (Rule 6(b)(v)).

4.1.3. *Rule 7 Risk of collision*. Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. The officer of M/V *Bravo* did not notice the risk of the collision until the officer of M/V *Alpha* called him (Rule 7(a)). However, he should have detected the targets, and have noticed the risk of collision. He changed the range scale of the radar occasionally and this did not enable him to detect M/V *Bravo* (Rule 7(b)). Moreover, when he changed the range scale, he needed to modify some other settings of the radar to the range that was neglected. This might be a reason why he did not detect M/V *Alpha* (Rule 7(c)).

4.1.4. *Rule 8 Action to avoid collision*. In case of any collision situation, the most important action is to prevent the collision regardless of being give-way vessel or stand-on vessel. Therefore, the officer of M/V *Bravo* should not have spent valuable

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

time trying to plot his position on the paper chart when the officer of M/V *Alpha* called him to ask his intention. This may have prevented consideration of an evasive manoeuvre (Rule 8(a)).

As he was fully concentrating on the vessels approaching from the starboard bow and he did not notice M/V *Alpha*, he could not take any effective action in ample time (Rule 8(c)). Moreover, when he noticed the starboard side light of M/V *Alpha* at a very close distance he could have slackened his speed to gain more time to assess the situation and take effective action for the purpose of taking more action and avoiding any probable collision by gaining more time (Rule 8(e)). In that respect, the officer of M/V *Bravo* violated COLREG Rule 8.

4.1.5. *Rule 17 Action by stand-on vessel.* In case of any collision situation each vessel should take evasive action to prevent collision. Though the priority of taking evasive action is on the give-way vessel, stand-on vessels should take the best action to avoid collision, when it becomes apparent that the other vessel is not taking action or when the two vessels are so close that action by the give-way alone will not be sufficient. The officer of M/V *Bravo* did not take any action as stand-on vessel. In that respect, M/V *Bravo* violated COLREG rule 17. A time chart of the actions taken by M/V *Bravo* is given in Table 3.

5. APPLICATION OF FRACTION DEFECTIVE MANAGEMENT (FDM).

Hierarchical design is used in GF-AHP. Objectives, criteria and alternatives are placed in the hierarchy. All criteria assessed in the court judgment process are discussed by field experts. The main criteria such as Rule 5 (C_1), Rule 6 (C_2), Rule 7 (C_3), Rule 8 (C_4), Rule 16 (C_5), Rule 17 (C_6) are confirmed to analyse their impact on alternatives. Then the survey is applied to seven decision makers (DM). Four of them are master mariners, two of them are academicians whose research area is marine accident analysis and one of them is a VTS operator. Figure 14 shows the corresponding hierarchical design of the FDM.

The GF-AHP approach is employed to determine the weights of criteria and alternatives. In the application process of the GF-AHP approach, a pairwise comparison table is formed. In the first step of the F-AHP approach, weights and priorities are compared for the each criterion using a pairwise fuzzy extension of Saaty's 1–9 scale (Table 4).

In Table 5, the criteria and their symbols are expressed. The GF-AHP approach is applied to calculate weights of alternatives for each criterion. Table 6 shows the alternatives for the track selection and their symbols.

For the decision process, the pairwise comparison survey was conducted and reported as follows. The individual fuzzy judgment matrices which assesses criteria-to-criteria comparison are presented in Table 7. Lambda (λ) is the expertise priority of the decision maker based on the time spent in this industry. The individual fuzzy priority vector and aggregated weight vector are depicted in Table 8. Decision makers usually find that Rule 8 is the most important factor and that lookout is the second crucial indicator.

The mean aggregated weight (MAW) is calculated for each criteria as 0·31, 0·11, 0·13, 0·35, 0·10 and 0·06 respectively (Table 9). To compute the aggregated weight vector, expert priority vector of decision makers (λ) is multiplied by the individual

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

Table 4. Membership function of linguistic scale.

Fuzzy number	Linguistic scales	Membership function	Inverse
$\tilde{A}_1$	Equally important	(1,1,1)	(1,1,1)
$\tilde{A}_2$	Moderately important	(1,3,5)	(1/5,1/3,1)
$\tilde{A}_3$	More important	(3,5,7)	(1/7,1/5,1/3)
$\tilde{A}_4$	Strongly important	(5,7,9)	(1/9,1/7,1/5)
$\tilde{A}_5$	Extremely important	(7,9,9)	(1/9,1/9,1/7)

Table 5. The criteria for the model of marine accident analysis and their symbols.

Criteria	The symbols of each criterion
Rule 5 Look-out	C_1
Rule 6 Safe Speed	C_2
Rule 7 Risk of collision	C_3
Rule 8 Action to avoid collision	C_4
Rule 16 Action by give-way vessel	C_5
Rule 17 Action by stand-on vessel	C_6

Table 6. The alternatives for the model of marine accident analysis and their symbols.

Alternatives	The symbols of each alternatives
Motor Vessel *Alpha*	A_1
Motor Vessel *Bravo*	A_2

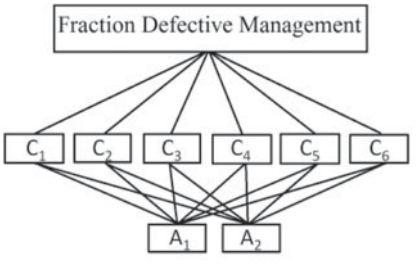


Figure 14. Hierarchical design of the fraction defective management.

priority vector of each decision maker. The result is consistent since the CCI is 0·23 less than the threshold of 0·37.

Then, similar steps are followed for alternatives. Table 10 indicates the aggregated fuzzy judgment matrix under each criterion that is calculated from the decision makers' individual fuzzy judgment matrices. Consistency control is not applied to the alternatives because there are two vessels (M/V *Alpha* and M/V *Bravo*) involved in the collision. Thus, when n = 2 it is accepted that it is totally consistent (Duru et al., 2012).

Table 11 indicates the final outputs of the FDM problem. FDs of the vessels are found to be 57% for M/V *Bravo* while for M/V *Alpha* it is 43%. The difference between

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

Table 7. The individual fuzzy judgment matrix for criteria of marine accident analysis.

	C_1	C_2	C_3	C_4	C_5	C_6
DM_1 with $\lambda = 0{\cdot}11$						
C_1	(1,1,1)	(1/5,1/3,1)	(5,7,9)	(1/5,1/3,1)	(1,3,5)	(3,5,7)
C_2	(1,3,5)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,3,5)	(1/5,1/3,1)
C_3	(1/9,1/7,1/5)	(1,3,5)	(1,1,1)	(1,3,5)	(1,3,5)	(1/7,1/5,1/3)
C_4	(1,3,5)	(3,5,7)	(1/5,1/3,1)	(1,1,1)	(3,5,7)	(1/9,1/7,1/5)
C_5	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(1/5,1/3,1)
C_6	(1/7,1/5,1/3)	(1,3,5)	(1/5,1/3,1)	(1/9,1/9,1/7)	(1,3,5)	(1,1,1)
DM_2 with $\lambda = 0{\cdot}25$						
C_1	(1,1,1)	(1/7,1/5,1/3)	(3,5,7)	(1,3,5)	(1,3,5)	(3,5,7)
C_2	(3,5,7)	(1,1,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)
C_3	(1/7,1/5,1/3)	(1,3,5)	(1,1,1)	(1/7,1/5,1/3)	(1,3,5)	(3,5,7)
C_4	(1/5,1/3,1)	(3,5,7)	(3,5,7)	(1,1,1)	(3,5,7)	(7,9,9)
C_5	(1/5,1/3,1)	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1,1,1)	(1,3,5)
C_6	(1/7,1/5,1/3)	(1,3,5)	(1/7,1/5,1/3)	(1/9,1/9,1/7)	(1/5,1/3,1)	(1,1,1)
DM_3 with $\lambda = 0{\cdot}11$						
C_1	(1,1,1)	(1/5,1/3,1)	(5,7,9)	(3,5,7)	(1/5,1/3,1)	(1,3,5)
C_2	(1,3,5)	(1,1,1)	(1,3,5)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1,3,5)
C_3	(1/9,1/7,1/5)	(1/5,1/3,1)	(1,1,1)	(1/7,1/5,1/3)	(1,3,5)	(3,5,7)
C_4	(1/7,1/5,1/3)	(5,7,9)	(3,5,7)	(1,1,1)	(5,7,9)	(3,5,7)
C_5	(1,3,5)	(1,3,5)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1,1,1)	(1/7,1/5,1/3)
C_6	(1/5,1/3,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/7,1/5,1/3)	(3,5,7)	(1,1,1)
DM_4 with $\lambda = 0{\cdot}14$						
C_1	(1,1,1)	(1,3,5)	(5,7,9)	(1,3,5)	(1/5,1/3,1)	(3,5,7)
C_2	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1/7,1/5,1/3)	(1,3,5)	(1,3,5)
C_3	(1/9,1/7,1/5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(3,5,7)	(1,3,5)
C_4	(1/5,1/3,1)	(3,5,7)	(1,3,5)	(1,1,1)	(5,7,9)	(5,7,9)
C_5	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1,1,1)	(7,9,9)
C_6	(1/7,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/9,1/9,1/7)	(1,1,1)
DM_5 with $\lambda = 0{\cdot}14$						
C_1	(1,1,1)	(1,3,5)	(3,5,7)	(1,3,5)	(1/5,1/3,1)	(1,3,5)
C_2	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/7,1/5,1/3)
C_3	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(3,5,7)
C_4	(1/5,1/3,1)	(1,3,5)	(1,3,5)	(1,1,1)	(1,3,5)	(5,7,9)
C_5	(1,3,5)	(3,5,7)	(1/5,1/3,1)	(1/5,1/3,1)	(1,1,1)	(7,9,9)
C_6	(1/5,1/3,1)	(3,5,7)	(1/7,1/5,1/3)	(1/9,1/7,1/5)	(1/9,1/9,1/7)	(1,1,1)
DM_6 with $\lambda = 0{\cdot}11$						
C_1	(1,1,1)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)	(1,3,5)
C_2	(1/5,1/3,1)	(1,1,1)	(1,3,5)	(1/7,1/5,1/3)	(1,3,5)	(1,3,5)
C_3	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(3,5,7)	(1,3,5)
C_4	(1/5,1/3,1)	(3,5,7)	(1,3,5)	(1,1,1)	(7,9,9)	(5,7,9)
C_5	(1/5,1/3,1)	(1/5,1/3,1)	(1/7,1/5,1/3)	(1/9,1/9,1/7)	(1,1,1)	(1,3,5)
C_6	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1,1,1)
DM_7 with $\lambda = 0{\cdot}14$						
C_1	(1,1,1)	(1,3,5)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)
C_2	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(1,3,5)	(1,3,5)
C_3	(1/5,1/3,1)	(1,3,5)	(1,1,1)	(1/5,1/3,1)	(1,3,5)	(1,3,5)
C_4	(1/7,1/5,1/3)	(1/5,1/3,1)	(1,3,5)	(1,1,1)	(7,9,9)	(5,7,9)
C_5	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/9,1/9,1/7)	(1,1,1)	(1,3,5)
C_6	(1/5,1/3,1)	(1/5,1/3,1)	(1/5,1/3,1)	(1/9,1/7,1/5)	(1/5,1/3,1)	(1,1,1)

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

Table 8. The individual fuzzy priority vector of decision-makers and aggregated weight vector for criteria of marine accident analysis.

	C1	C2	C3	C4	C5	C6
DM_1	(0·23,0·22,0·24)	(0·11,0·11,0·13)	(0·13,0·14,0·13)	(0·19,0·18,0·17)	(0·06,0·05,0·08)	(0·28,0·29,0·26)
DM_2	(0·23,0·25,0·24)	(0·08,0·08,0·10)	(0·14,0·15,0·14)	(0·40,0·36,0·33)	(0·09,0·10,0·12)	(0·06,0·05,0·06)
DM_3	(0·21,0·22,0·24)	(0·12,0·15,0·16)	(0·10,0·10,0·11)	(0·40,0·36,0·31)	(0·09,0·10,0·10)	(0·08,0·08,0·09)
DM_4	(0·27,0·28,0·28)	(0·11,0·14,0·15)	(0·09,0·10,0·11)	(0·39,0·33,0·31)	(0·11,0·10,0·10)	(0·03,0·03,0·04)
DM_5	(0·23,0·26,0·25)	(0·08,0·07,0·09)	(0·13,0·12,0·12)	(0·25,0·28,0·27)	(0·24,0·22,0·21)	(0·08,0·06,0·05)
DM_6	(0·27,0·34,0·32)	(0·12,0·14,0·15)	(0·11,0·10,0·12)	(0·37,0·32,0·30)	(0·07,0·05,0·06)	(0·05,0·04,0·06)
DM_7	(0·31,0·36,0·32)	(0·15,0·16,0·18)	(0·15,0·16,0·18)	(0·26,0·20,0·18)	(0·08,0·06,0·08)	(0·06,0·05,0·06)
Agg. Weight	(0·26,0·31,0·30)	(0·11,0·12,0·14)	(0·13,0·14,0·15)	(0·33,0·33,0·30)	(0·10,0·10,0·12)	(0·07,0·07,0·08)

Table 9. The aggregated fuzzy judgment matrix for criteria of marine accident analysis.

	C1	C2	C3	C4	C5	C6	MAW
C1	(1·00,1·00,1·00)	(0·43,0·93,1·76)	(3·11,5·27,7·33)	(1·10,2·66,4·53)	(0·54,1·28,2·68)	(1·73,3·87,5·92)	(0·31)
C2	(0·57,1·08,2·34)	(1·00,1·00,1·00)	(0·45,1·00,2·24)	(0·19,0·30,0·53)	(0·43,0·93,2·24)	(0·43,0·93,1·92)	(0·11)
C3	(0·14,0·19,0·32)	(0·45,1·00,2·24)	(1·00,1·00,1·00)	(0·21,0·36,0·81)	(1·32,3·41,5·44)	(1·39,2·85,4·35)	(0·13)
C4	(0·22,0·38,0·91)	(1·89,3·35,5·28)	(1·24,2·81,4·71)	(1·00,1·00,1·00)	(3·63,5·88,7·58)	(3·33,4·61,5·68)	(0·35)
C5	(0·37,0·78,1·86)	(0·52,1·07,2·34)	(0·18,0·29,0·76)	(0·13,0·17,0·28)	(1·00,1·00,1·00)	(1·14,2·32,3·59)	(0·10)
C6	(0·17,0·26,0·58)	(0·52,1·07,2·34)	(0·17,0·26,0·58)	(0·11,0·14,0·19)	(0·28,0·43,0·88)	(1·00,1·00,1·00)	(0·06)
CCI = 0·23							

Table 10. The aggregated fuzzy judgment matrix for alternatives of marine accident analysis under each criterion.

Criteria		A_1	A_2
C_1	A_1	(1,1,1)	(0·36,0·56,1·20)
	A_2	(0·83,2·24,4·16)	(1,1,1)
C_2	A_1	(1,1,1)	(0·36,0·56,1·20)
	A_2	(0·67,1·73,3·34)	(1,1,1)
C_3	A_1	(1,1,1)	(0·43,0·72,1·32)
	A_2	(0·76,1·84,3·47)	(1,1,1)
C_4	A_1	(1,1,1)	(0·56,0·91,1·42)
	A_2	(0·57,1·07,2·15)	(1,1,1)
C_5	A_1	(1,1,1)	(0·33,0·60,1·09)
	A_2	(0·91,1·67,3·01)	(1,1,1)
C_6	A_1	(1,1,1)	(9·00,9·00,9·00)
	A_2	(0·11,0·11,0·11)	(1,1,1)
C_7	A_1	(1,1,1)	(0·11,0·11,0·11)
	A_2	(9·00,9·00,9·00)	(1,1,1)

Table 11. Final assessment of alternatives of marine accident analysis.

Weight	C_1 0·26	C_2 0·11	C_3 0·20	C_4 0·31	C_5 0·10	C_6 0·04	Alternative priority weight
A_1	0·29	0·36	0·34	0·48	0·93	0·07	0·43
A_2	0·71	0·64	0·66	0·52	0·07	0·93	0·57

Table 12. Changes of the responsibilities.

	First Judgement	Expert consultation	Percentage of Responsibility Change
M/V *Alpha*	40%	43%	+ 7·5%
M/V *Bravo*	60%	57%	− 5·0%

the FDs is 14% after the expert consultation process. According to the official reports of the court judgment for this collision, FD of M/V *Alpha* is 40% and M/V *Bravo* is 60%, with a difference of 20%. The superiority of the FDM is quite explicit since the difference between the ranges of first judgment and expert consultation by using GF-AHP is 6%.

Table 12 indicates that this decision burdens the M/V *Bravo* with 5% more financial and legal obligations. Similarly, comparing to the first situation, FD of M/V *Alpha* has changed from 40% to 43%. This means M/V Alpha's responsibilities are increased by 7·5%. This proves that the conventional marine accident analysis is applied from a holistic point of view. Also, the complete assessment process involves human judgment that is limited and subject to bias.

6. CONCLUSION. In order to make professional judgments and fair decisions, FDM should be utilised for complex decision making situations. In this

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

research, the GF-AHP method is conducted for FDM on a simulated real collision. In the Simulator Centre of ITU, in front of the field experts, the same vessels were navigated, and collided again as occurred in real time. After an expert consultation, all contributory causes were determined by the experienced captains, pilots and as well as the academics. Contributions of the COLREG rules and regulations were discussed to find the values of the FDs.

If available, VDR data are always considered as a primary source of evidence in the courts. Even though the simulation process is omitted, it is obvious that all judges and experts use the VDR records. In that respect, the systematic F-AHP approach is more convenient than the regular basis as the method provides an explicit opportunity of prioritising all criteria that caused the accident. Thus, each criterion is criticised in a stepwise manner instead of a holistic perspective. Moreover, by using the main bridge simulator, we can visualise it with real data to make the experts feel the event. As a result, we combined the GF-AHP method and simulator by using real VDR records that enabled the experts to imagine the collision and assess the criteria much more clearly than the holistic assessment.

During the marine accident judgment process, FDM involves the insurance companies, ship owners, banks, personnel of the vessels, etc. Judgements can burden the participants with large financial losses. Therefore, the decision-making process is thought very significant, and should be able to be conducted in all cases. The empirical results prove that experts decide the FDs by looking at the big picture rather than fractionating the defectives in a stepwise manner. Human judgment is limited, and can be manipulated by cognitive bias. In this study, we proposed a decision support model for FDM that classifies the problem, and defines the final result by the consensus of the experts. We also hope to improve the investigations of the marine accident.

REFERENCES

Aguarón, J. and Moreno-Jiménez, J.M. (2003). The geometric consistency index: Approximated thresholds. *European Journal of Operational Research*, **147**, 137–145.

Bellman, R.E. and Zadeh, L.A. (1977). Local and fuzzy logics, *Modern Uses of Multiple- Valued Logic*, J.M. Dunn and G. Epstein (eds.), 103–165.

Buckley, J.J. (1985). Fuzzy Hierarchical Analysis. *Fuzzy Sets and System*, **17**, 233–247.

Bulut, E., Duru, O., Kececi, T. and Yoshida, S. (2012). Use of consistency index, expert prioritization and direct numerical inputs for generic fuzzy-AHP modeling: A process model for shipping asset management. *Expert Systems with Applications*, **39**(2), 1911–1923.

Cakir, O. and Canpolat, M.S. (2008). A web-based decision support system for multi-criteria inventory classification using fuzzy AHP methodology. *Expert Systems with Applications*, **35**, 1367–1378.

Chang, D.Y. (1996). Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research*, **95**, 649–655.

COLREGS (1972). [with amendments adopted from December 2009]. *Convention on the International Regulations for Preventing Collisions at Sea*. London: International Maritime Organization.

Crawford, G. and Williams, C. (1985). A note on the analysis of subjective judgment matrices. *Journal of Mathematical Psychology*, **29**, 387–405.

Duru, O., Bulut, E. and Yoshida, S. (2012). Regime switching fuzzy AHP model for choice-varying priorities problem and expert consistency prioritization: A cubic fuzzy-priority matrix design. *Expert Systems with Applications*, **39**, 4954–4964.

Laarhoven, P.J.M. and Pedrycz, W. (1983). A fuzzy extension of Saaty's priority theory. *Fuzzy Sets and Systems*, **11**, 229–241.

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press

Lee, M., Pham, H. and Zhang, X. (1999). A methodology for priority setting with application to software development process. *European Journal of Operational Research*, **118**, 375–389.
Leung, L.C. and Cao, D. (2000). On consistency and ranking of alternatives in fuzzy AHP. *European Journal of Operational Research*, **124**, 102–113.
Saaty, T.L. and Vargas, L.G. (1987). Uncertainty and rank order in the analytic hierarchy process. *European Journal of Operational Research*, **32**, 107–117.
Saaty, T.L. (1980). *The analytic hierarchy process*. New York: McGraw- Hill.
Weck, M., Klocke, F., Schell, H. and Ruenauver, E. (1997). Evaluating alternative production cycles using the extended fuzzy AHP method. *European Journal of Operational Research*, **100**, 351–366.
Zadeh, L.A. (1975). The concept of linguistic variable and its application to approximate reasoning-I. *Information Sciences*, **8**, 199–249.
Zadeh, L.A. (1965). Fuzzy sets. *Information and Control*, **8**(3), 338–353.

APPENDIX: THE MAIN DATA SOURCES FOR MARINE ACCIDENTS

Global Integrated Shipping Information System (GISIS)
IMO MSC-MEPC.3/Circ.3
IMO FSI 20/INF.17
FSI and IMO Council documents on IMODOCS
IMO Performance Indicators
International Shipping Facts and Figures – Information Resources on Trade, Safety, Security and the Environment
Lloyd's Casualty Returns available from Lloyd's Register Library
LMIU Casualty Reports
IHS Fairplay World Casualty Statistics
International Union of Marine Insurers (IUMI)
European Maritime Safety Agency: Annual Maritime Accident Review
ShipPax Information
Marine Casualty Profiles International Maritime Statistics Forum
Wally Mandryk Lloyd's List Intelligence
Australian Transport Safety Bureau (ATSB)
Transportation Safety Board of Canada (TSBC)
BEAmer- The Bureau d'enquêtes sur les événements de mer
Dutch Transport Safety Board
Transport Accident Investigation Commission (TAIC)
Swedish Accident Investigation Board (SHK)
UK Marine Accident Investigation Branch (MAIB)
Marine Accident Reporting Scheme (MARS)
US National Transportation Safety Board (NTSB)

https://doi.org/10.1017/S0373463314000514 Published online by Cambridge University Press