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Risk analysis of break-in-two accident of ships using fuzzy DEMATEL method

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ABSTRACT

Structural damage accidents that lead to disastrous results are an important problem in the maritime industry. However, as a sectoral requirement, factors causing break-in-two accident of ships are not clearly defined. In this study, an alternative risk analysis approach based on 18 factors that trigger ship structural damage was presented in order to prevent break-in-two accident of ships. These factors were determined by using literature review and they were analyzed using fuzzy DEMATEL (Decision Making Trial and Evaluation Laboratory), a widely used method to find out the cause and effect relationship among. Nine factors for cause and effect groups were investigated separately. According to the analyses, in the cause group, cargo specification (0.87), competency of the crew involved in the cargo handling operation (0.78), compliance with international rules, regulations and guidelines about ship safety and cargo operation (0.63), heavy weather (0.59) were identified as the most critical factors. However, among the effect group, cargo stowage and operational plan (3.30), ship's age, hull and structure condition (3.31) and complying with the ship's planned maintenance system (2.67) were indicated as the most highly significant factors. Accordingly, some recommendations for using fuzzy DEMATEL approach were made considering ship structural accidents and preventive measures.

1. Introduction

One of the most important elements of safe maritime cargo transportation is to maintain the structural integrity together with stability of the ship, and one of the most critical processes in ship operations is cargo handling. As a matter of fact, faulty cargo handling operations may cause damages to the cargo and ship structure, loss of the ship stability, sinking of the ship, and break-in-two accident of ships which finally result in loss of life, injuries, marine pollution and financial loss. Ships are designed within the limits that maintain their structural integrity throughout their operational life. Exceeding these limits causes great stresses and, consequently, major structural damage. When ship's hull crack and its break-in-two accident are reviewed, mid-ship region is seen as the region of crack occurrence since the BM (Bending Moment) is always greater at the mid-ship. Ship hull is designed to withstand static loads including ship weight and buoyancy of water and dynamic loads caused by waves and ship movements. The buoyancy force is more at the mid-ship region as the submerged volume and the BM are always greater at this region. Longitudinal strength of the hull is designed considering BM limit at the mid-ship. The bottom plate of the ship is exposed to tensile when the ship is sagging and the main deck of the ship is exposed to tensile when the ship is hogging. If yield strength limit of the hull material is exceeded during sagging or hogging, cracks can occur at mid-ship region and propagate through the hull. Propagation of cracks results in break-in-two accident of the ships (Chakraborty, 2014). Loading and discharging operations are one of the most significant processes for the structural integrity and hull strength of the ship. Improper cargo handling operations increase stress on the hull and reduce the resistance of the ship against dynamic loads at sea. Therefore, steps of cargo plan should be followed properly and SF (Shear Force) and BM limits of the ship should not be exceeded during cargo handling operations. There have been a significant number of ships broken-in-two due to incorrect cargo handling operations. That's why cargo operations require correct planning, correct cargo handling and great attention. During cargo loading and discharging operations, the limits of ship's SF and BM are not exceeded. A safe cargo handling operation and protection of the ship structure is dependent on the permissible stress not to be exceeded. Ship crew and port personnel should be in constant coordination at cargo operation planning process and during cargo handling operation. Before commencing cargo handling operations, loading master of the port and chief officer of the ship must agree on loading/discharging method and speed of loading/discharging. Cargo operation plan, ballast pumping

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rate and cargo loading/unloading rate must be prepared in a way that does not create undue stress to the ship structure (Taylor, 1992; House, 2005). Continuous and effective communication between the ship and the shore during cargo handling operations must be established during cargo operation according to the IMO (International Maritime Organization) Ship/Shore Safety Check List (IMO, 1997). Officer of the cargo watch in charge should carefully monitor any deviation from the plan throughout the operation and ensure that the loading/discharging operation and the ballast procedure are synchronized (Hess and Hess, 2009). International rules, regulations and guidelines provide information about requirements, ship structure and stability standards, safe cargo handling operations and safe cargo transportation for different types of ships (Barras, 2001; IMO, 2007a, 2007b; 2008, 2011; 2016, 2018; Pepper, 2018). Survey standards, evaluation and repair of ship hull structure, fatigue inspections of ship structural details were also comprehensively described in publications of International Association of Classification Societies (IACS, 2001, 2005 and 2012). There are also studies in scope of ship structural analysis in literature. Paik and Frieze (2001) reviewed reliability and safety of ship's structural design methods focusing on collapse of ship hull, and recommended technologically advanced design procedures. Yan et al. (2016) proposed a method to assess metal fatigue in ship structural details which was also addressed in another study about management of ship structural fatigue (Okawa et al., 2006). Ozguc (2017) focused on theoretical calculations of fatigue assessment. Andersen (1998) studied on initiation and growth of fatigue crack in ships structure. In this study, novel fatigue analysis tools were suggested to develop a fatigue resistant slot design. Nguyen and Oterkus (2020) focused on brittle cracks on a ship structure exposed to variable loading conditions and used a new method to assess the structural strength of ship. Hong (2008) proposed computational methods that can be used to analyze the structure of the ship in case of collision and grounding. Great efforts have been made in the maritime industry to eliminate marine accidents due to their severe consequences such as loss of life, severe injuries, marine pollution as well as damage to cargo and ship. Lots of research articles have been focused on maritime accidents to fill the gaps in the field (Eliopoulou et al., 2016; Primorac and Parunov, 2016; Chen, et al., 2019; Kuzu et al., 2019; Luo and Shin, 2019).

It is possible to find many accident reports and studies related to the ship structural damage accidents in the literature. Sumi (2019) reviewed the chronological history of ship's hull crack in mid-ship section accidents focusing on technological developments and international regulations. He also suggested what to be studied to avoid structural failure of ships. MAIB (2008) published investigation report on the structural failure of MSC Napoli which was a 4419 TEU (Twenty Empty Units) container vessel encountering heavy weather condition and suffering hull failure while transiting the English Channel. A similar accident was experienced at Indian Ocean. Mol Comfort was an 8000 TEU large container ship that experienced crack in mid-ship section and broke in two while sailing to Port of Jeddah. This accident was analyzed and causes of the accident were reported by Committee on Large Container Ship Safety in Japan (Sumi et al., 2015). Stellar Daisy, Very Large Ore Carrier (VLOC), experienced a catastrophic structural failure in 2017 and it caused loss of 24 crew members lives and the whole vessel. Stellar Daisy was constructed as Very Large Crude Carrier (VLCC) in 1993 and she was converted to VLOC in 2009 (Blenkey, 2019). The last ship structural failure accident was encountered on the 15th of January 2021. MV Arvin, a 46-year-old dry bulk carrier, broke in two at Turkey's Black Sea coast whilst transiting from Port of Poti to Port of Burgas (Goddard, 2021). Zhang and Li (2017) analyzed the effects of sea states on ship accidents using ten-year- ship accident dataset of IMO and classified 755 weather related accidents of ships according to initial events. 25,4% of initial events were stated as hull damage. Wang et al. (2019) proposed voyage optimization to minimize the structural fatigue accumulation in ships. In another study, common ship structure failures were addressed. Indents, corrosion, metal fatigue cracks and buckling of plates were described as common ship structure failures. To address ship structural failures, the 3C (Cause, Consequence, Cure) method was proposed. The first step of the 3C is to identify reason of the ship structural failure while the second step of the 3C is to identify consequences of the ship structural failure and the last step of the 3C is to cure the ship structure (Raju and Premanandh, 2018). Nair et al. (2017) proposed an age based crack assessment criteria taking inducement factors into account which trigger cracks in the hull structure of the ship at the early stage. In the study, material properties, design, welding process, temperature, metal fatigue, corrosion and accidents were defined as inducement factors and causes of inducement factors were introduced using references. The ships were then classified by age, and a circular data visualization was developed for each age category showing inducement factors and reasons. Ship's age and NASF (Non-Accidental Structural Failure) were addressed in a statistical review study. It was concluded that the accident frequency of ships increased as ships reached the age of ten (Primorac and Parunov, 2016).

Today, one of the most dangerous types of marine accidents is break-in-two accident of ships as a result of structural damage, and such accidents still cannot be prevented. Why such a serious accident cannot be prevented despite new technologies, international regulations and periodic inspections? What are the root cause factors affecting this type of accident and what is the relationship between them? To be honest, the factors that trigger the accident have not been clearly revealed and analyzed in the literature. This study addresses the factors that trigger structural damage and break-in-two accident of ships. Although there are different types of ship structural damage accidents to be analyzed, this study is limited to analysis of those factors that trigger break-in-two accident of ships.

Although many studies on ship structural analysis and ship structural damage accidents encountered in the literature, a detailed analysis of the factors that trigger hull damage and break-in-two accident of ships has been made quite limited. In order to fill this gap in the literature, the causal relationships and weighting of the factors that trigger break-in-two accident of ships were analyzed using the fuzzy DEMATEL method which was used applying the fuzzy logic to multi-criteria decision making method. This method, which has been used in various studies to analyze the cause-effect relationship between factors, was used for the first time to analyze ship structural damage accidents. In the second chapter, this method is an integration of fuzzy and DEMATEL approaches.

In this study, by using fuzzy DEMATEL method, the factors affecting ship structural damage were determined and an appropriate methodology was proposed to analyze structural damage problem and break-in-two accident of ships. Accordingly, the factor evaluations based on the data collected by planning flow processes with the fuzzy DEMATEL approach are defined in the third section.

2. Method

Approaches such as 3C, NASF, voyage optimization, IMO's statistical data set of ship accidents were preferred in ship structural damage and accident studies in the literature, as mentioned in the introduction of this study. It was evaluated that these approaches are not sufficient in defining and analyzing the critical factors that trigger ship breakage. As a matter of fact, it is seen that these approaches are mostly used in the evaluation of processes such as material selection, metal fatigue, corrosion, sheering force and bending moment. In this study, fuzzy DEMATEL method, which is a combination of fuzzy and DEMATEL approaches, was preferred for risk impact analysis of critical factors.

The DEMATEL approach is defined as an efficient tool designed to identify the meaning of specifications and the current configuration and relationship between the parameters; in which this method is based on a binary diagram dividing the requirements that cause problems into groups of cause and effect (Gabus and Fontela, 1972). The most important aspect which distinguishes the DEMATEL approach from other decision-making approaches with multiple parameters is the ability to evaluate the relationship between factors that influence the issue and distribution of the factors according to the status of the connection and interactions between current factors. (Akyuz and Celik, 2015; Tseng and Yuan Hsu Lin, 2009). Ozdemir et al. (2016) investigated marine pollution from various operations of ships using DEMATEL method. Massami and Manyasi (2019) applied DEMATEL method to assess the challenges in training on board in Tanzania. DEMATEL method has been integrated with other methods in various studies. Wang et al. (2018) integrated DEMATEL and ISM (Interpretive Structure Modelling) to evaluate influencing factors of safety in coal mine production. Lia et al. (2019) also combined and used DEMATEL, ISM (Interpretive Structure Modelling) and BN (Bayesian Network) methods to analyze the factors causing network of buried urban gas pipeline accident. DEMATEL and BN methods were integrated to develop a dynamic quantitative risk evaluation for assessment of accident probabilities caused by leakage on offshore platforms (Meng et al., 2019). In another risk assessment study, Mentes et al. (2015) used DEMATEL together with FSA (Formal Safety Assessment). Vujanovic et al. (2012) used DEMATEL and ANP (Analytic Network Process) together to evaluate maintenance management indicators of vehicle fleet. Using a similar method, container terminals performances were evaluated using fuzzy AHP (Analytic Hierarchy Process) DEMATEL method (Venkatasubbaiah et al., 2014). Karuppiah et al. (2020) also used fuzzy ANP (Analytic Network Process) DEMATEL for evaluation of faulty behavior risks.

The use of fuzzy DEMATEL in the solutions of different engineering problems makes it possible to obtain a set of applicable and practical alternatives by considering independent and stochastic evaluations within a certain analytical dimension (Akyuz and Celik, 2015; Govindan et al., 2015; Karuppiah et al., 2020; Luthra et al., 2016; Tseng and Yuan Hsu Lin, 2009; Wu and Lee, 2007). In this method, fuzzy sets were combined with the DEMATEL system that is related to complex problem solution based on linguistic. It was ensured that the evaluations of the decision-making community were made more appropriate for the application of fuzzy logic to the DEMATEL system by using linguistic variables in communicating ambiguity on the basis of this logic (Akyuz and Celik, 2015; Tseng and Yuan Hsu Lin, 2009; Wu and Lee, 2007). Tseng and Yuan Hsu Lin (2009) developed a cause and effect model for management of solid waste using fuzzy DEMATEL method. Akyuz and Celik (2015) evaluated hazards of gas free operation in oil tankers using fuzzy DEMATEL method. They developed the method by using type-2 fuzzy sets instead of type-1 and they used the developed method in another study. Celik and Akyüz (2016) analyzed causal factors and effects of a real ship collision using DEMATEL method with interval type-2 fuzzy sets. Seker and Zavadskas (2017) proposed a simplified risk assessment model to examine occupational hazards on construction sites using fuzzy DEMATEL method. Başhan and Demirel (2019) made use of fuzzy DEMATEL method to assess operational malfunctions of marine boilers. Interactions of factors affecting situation awareness were investigated using fuzzy DEMATEL approach (Mohammadfam et al., 2019).

2.1. Fuzzy sets

Fuzzy reasoning, developed in 1965 by Lotfi A. Zadeh, is an effective instrument for dealing with the vagueness, ambiguity and complexity of decision-making in human judgement and evaluation. Decision-making challenges in the real world require imprecision since priorities, limitations and future actions are not precisely defined (Zadeh, 1965). It is easier to translate linguistic words into fuzzy numbers instead of mixing different perceptions, thoughts, ideas, and motives of a person or group of decision maker. Therefore, in fact, during decision-making, it is important to generate fuzzy numbers. A triangular fuzzy number can be defined in this context as a triplet $\widetilde{A} = (l, m, u)$ where l, m and u denote the lower, medium and upper numbers of the fuzzy sets. The membership function of a triangular fuzzy number can be expressed as follows.

$$\mu_{\widetilde{A}} = \begin{cases} 0, & x < 1 \\ (x-l)/(m-l), & l \leq x \leq m \\ (u-x)/(u-m), & m \leq x \leq u \\ 0 & x \geq u \end{cases}$$

Fig. 1 displays a triangular fuzzy number in the light above. In accordance with Table 1, the corresponding relationship between the linguistic words and triangular fuzzy numbers can be calculated (see Fig. 2).

For either of the two fuzzy triangular numbers, $\widetilde{A}_1 = (l_1, m_1, u_1)$ and $\widetilde{A}_2 = (l_2, m_2, u_2)$. It is possible to characterize the statistical estimation of them as follows:

Aggregation of triangular fuzzy numbers between them;

$$\widetilde{A}_1 + \widetilde{A}_2 = (l_1 + l_2,\ m_1 + m_2,\ u_1 + u_2)$$

Subtraction of the triangular fuzzy numbers between them;

$$\widetilde{A}_1 - \widetilde{A}_2 = (l_1 - l_2,\ m_1 - m_2,\ u_1 - u_2)$$

Multiplication among the fuzzy triangular numbers;

$$\widetilde{A}_1 \times \widetilde{A}_2 = (l_1 \times l_2,\ m_1 \times m_2,\ u_1 \times u_2)$$

The arithmetic sense of the fuzzy triangular numbers;

$$k \times \widetilde{A}_1 = (k \times l_1,\ k \times m_1,\ k \times u_1),\ k > 0$$

$$\frac{\widetilde{A}_1}{k} = \left(\frac{l_1}{k}, \frac{m_1}{k}, \frac{u_1}{k}\right),\ k > 0$$

2.2. DEMATEL method

To resolve dynamic and detailed decision-making concerns, the DEMATEL approach was developed (Gabus and Fontela, 1972). It has been widely accepted as one of the best practical methods for finding cause and effect relationships between evaluated parameters. (Akyuz and Celik, 2015; Ozdemir, 2016). The method enables visualization problems to be analyzed and clarified (Tseng and Yuan Hsu Lin, 2009). The approach illustrates the relationship of interdependence between the variables as well as influential impact values. The basic steps of the DEMATEL process are briefly illustrated as follows:

Step 1For pair wise comparison, the purpose of the first step is to create an initial direct-relation matrix. A community of decision-makers who have problem-related expertise and experience is decided. They are then asked to determine the effects of each pair of variables. Thus, the decision maker's linguistic appraisal is translated to actual values. The direct-relation matrix is therefore defined. $A = [a_{ij}]$ where A is $n \times n$ non-negative matrix, a_{ij} indicates the direct

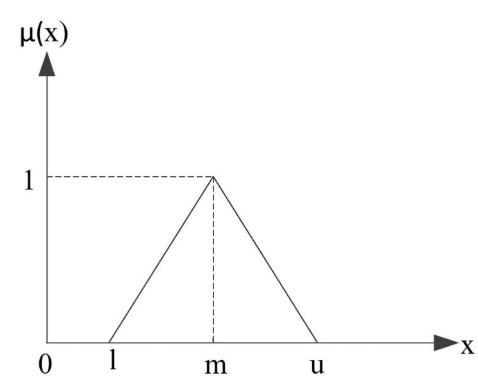

Fig. 1. Triangular fuzzy number.

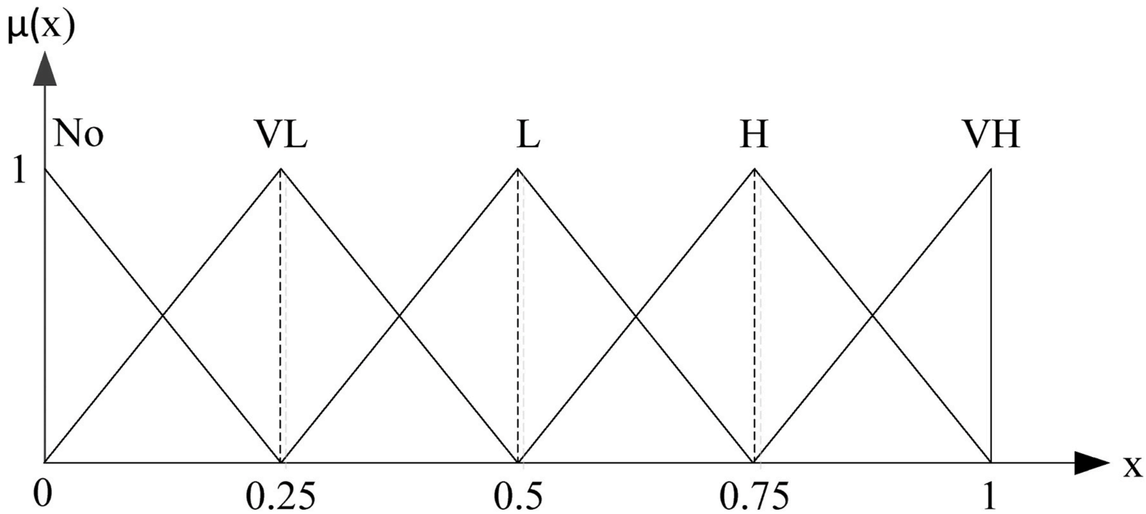

Fig. 2. Fuzzy ratings and their membership function >

Table 1
Corresponding relationship between linguistic terms and fuzzy numbers.

Linguistic terms	Triangular Fuzzy Numbers		
No influence (No)	0	0	0.25
Very low influence (VL)	0	0.25	0.5
Low influence (L)	0.25	0.5	0.75
High influence (ML)	0.5	0.75	1
Very high influence (HL)	0.75	1	1

impact of factor i on factor j; and when $i = j$, the diagonal elements $a_{ij} = 0$.

Step 2The initial direct-relation matrix is normalized in this step by comparing the variables.

Step 3The total-relation matrix (T) is calculated using the following equation where I point i outs nxn identity matrix. The element t_{ij} indicates the indirect factors that criterion i have on criterion j, so T gives the total relationship between the each factor pair.

$$T = D(I - D)^{-1}$$

Step 4In the fourth step, $\widetilde{r}_i$, and $\widetilde{c}_j$ are determined by using the following equations. In the formula, while $\widetilde{r}_i$, indicates direct and indirect effect totally given by criterion i to all other factors, $\widetilde{c}_j$ denotes the degree of affected impact.

$$r_i = \sum_{j=1}^{n} T_{ij}$$

$$c_j = \sum_{i=1}^{n} T_{ij}$$

When $i = j$, $\widetilde{r}_i + \widetilde{c}_j$ indicates all factors that are given and received by criterion i. That is, $\widetilde{r}_i + \widetilde{c}_j$ shows both criterion i's effect on the whole system and other system factors effect upon factor i. So, $\widetilde{r}_i + \widetilde{c}_j$ can indicate the importance degree that criterion i in the whole system. On the other hand, if the $\widetilde{r}_i$- $\widetilde{c}_j$ value is positive, the factor i will be a clear cause. If $\widetilde{r}_i$- $\widetilde{c}_j$ is negative, the factor will be a clear result clustered within the impact group (Akyuz and Celik, 2015; Demirel, 2020; Wu and Lee, 2007).

Step 5In the final step, a cause and effect relationship diagram is depicted according to the $\widetilde{r}_i + \widetilde{c}_j$ and $\widetilde{r}_i$- $\widetilde{c}_j$ values. Thus, the complex relationship between factors is easily visualized.

2.3. Integration of methods: fuzzy DEMATEL approach

In this portion, in order to assess critical hazards in ship structural damage and beak-in-two incidents, fuzzy sets and DEMATEL technique are combined. DEMATEL has been shown to be an intelligent decision-making approach to evaluate critical factors by dividing them into cause-effect groups, while fuzzy clusters are a method for dealing with uncertain judgments in the group decision-making process. The method's main steps are described as follows (Akyuz and Celik, 2015; Demirel, 2020; Mentes et al., 2015; Tseng and Yuan Hsu Lin, 2009).

Step 1- ***Selection of decision makers:*** In this stage, experts who have adequate knowledge and experience of the problem are consulted in order to obtain judgments.

Step 2- ***Determining criteria:*** In this section, in order to better analyze and assess, important factors are defined.

Step 3***: Obtaining evaluation of the decision makers and construction of fuzzy scale:*** In terms of linguistic variables, a pair wise comparison is obtained. The linguistic variable is then used on five fuzzy scales in accordance with (no influence, very low influence, low influence, high influence, and very high influence). Subsequently, relevant triangular fuzzy members are calculated. In addition, the fuzzy evaluations are converted into a crisp value that is defuzzified and aggregated.

Step 4- ***Generating direct-relation fuzzy matrix and normalized direct-relation fuzzy matrix:*** A normalized direct-relation fuzzy matrix is constructed in the presence of the initial direct-relation matrix. Thereafter, to turn the variables into comparable scales, the linear scale transformation is applied.

Step 5- ***Calculation of total relation fuzzy matrix:*** At the fifth step, the total-relation fuzzy matrix is calculated. The crisp case of the total-relation fuzzy matrix can be calculated using the formulas below:

$$\widetilde{T} = \lim_{k \to +\infty} (\widetilde{x}^1 + \widetilde{x}^2 + \ldots + \widetilde{x}^k)$$

where $\widetilde{t}_{ij} = (l''_{ij}, m''_{ij}, u''_{ij})$

$$\left[l''_{ij}\right] = x_l \times (I - x_l)^{-1}$$

$$\left[m''_{ij}\right] = x_m \times (I - x_m)^{-1}$$

$$\left[u''_{ij}\right] = x_u \times (I - x_u)^{-1}$$

Step 6- ***Analysis of the model:*** After having calculated matrix $\tilde{T}$, $\tilde{r}_i+\tilde{c}_j$ and $\tilde{r}_i-\tilde{c}_j$ are determined. In the formula, $\tilde{r}_i$and $\tilde{c}_j$ indicate the sum of the rows and columns of matrix $\tilde{T}$. While $\tilde{r}_i+\tilde{c}_j$ indicates the importance of factor *i* and $\tilde{r}_i-\tilde{c}_j$ shows the net effect of factor ***i***.

Step 7- ***Defuzzication process:*** In this step $\tilde{r}_i+\tilde{c}_j$ and $\tilde{r}_i-\tilde{c}_j$ are defuzzified by using COA (center of area) defuzzification method which is introduced by Ross (1995) to determine the values of BNP (best non-fuzzy performance). For a convex fuzzy number $\tilde{\delta}$, and real number z* corresponding to the center of area, can be determined by using the formulas below. (Akyuz and Celik, 2015).

$$z^* = \frac{\int \mu(z)zdz}{\int \mu(z)dz}$$

The BNP value of a fuzzy number $\tilde{G} = (l_{ij},\ m_{ij},\ u_{ij})$ can be found with following formula.

$$BNP_{ij} = \frac{u_{ij} - l_{ij} + m_{ij} - l_{ij}}{3} + l_{ij}$$

Step 8- ***Obtaining final output and building up cause and effect relation diagram:*** In the final step, the cause and effect relation diagram is explained by mapping the dataset of $\tilde{r}_i+\tilde{c}_j$ and $\tilde{r}_i-\tilde{c}_j$. Fig. 3 shows the flow diagram of the fuzzy DEMATEL method.

3. Case of approach

3.1. Step 1: selection of decision makers

To obtain evaluation, five decision makers who have enough knowledge and experience about the problem were determined as shipbuilding and structure surveyor, ship master, port loading master, naval architecture and marine engineer and academician.

3.2. Step 2: Determining criteria

Within the scope of the research model, to determine the criteria and alternatives and to obtain data sets, a literature review including international rules, regulations, standards and guidelines, academic studies, statistics, damage and accident reports about ship structure and stability, cargo handling operations and cargo transportation was conducted with the experts of the subject and the criteria for the structural damage problem of the ships were tried to be determined. As a result of the evaluations made, 18 main criteria shown in Table 2 were determined.

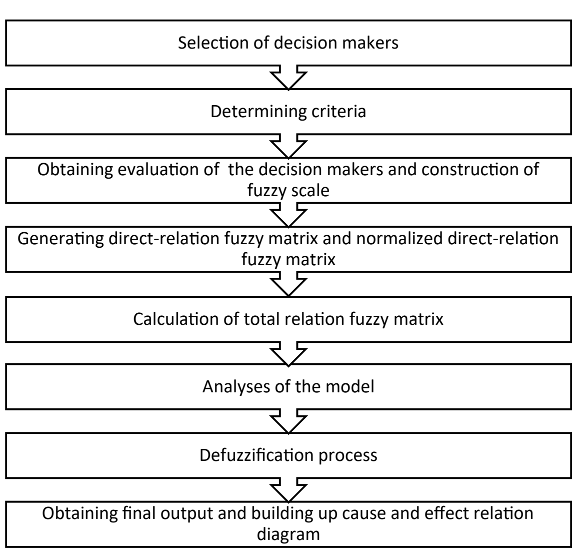

Fig. 3. Application flow diagram of the Fuzzy DEMATEL Method.

3.3. Step 3: Obtaining evaluation of the decision makers and construction of fuzzy scale

Linguistic assessment of the decision makers was obtained and shown in Table 3. Then, a fuzzy evaluation scale was created in order to transform the linguistic pairwise comparison opinions obtained from decision makers into triangular fuzzy numbers.

3.4. Step 4: Generating direct-relation fuzzy matrix and normalized direct-relation fuzzy matrix

In order to define the relations among the n criteria, an initial direct relation n × n matrix was constructed for decision makers' pair wise comparison.

$$d = \begin{bmatrix} 0 & \cdots & \tilde{d}_{n1} \\ \vdots & \ddots & \vdots \\ \tilde{d}_{1n} & \cdots & 0 \end{bmatrix}$$

Arithmetic mean of all of the decision makers' evaluations was used to establish the direct relation fuzzy matrix. Table 4 shows the direct relation fuzzy matrix.

The normalized fuzzy direct-relation matrix which is shown in Table 5 can be obtained using the following formula:

$$\tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right)$$

where

$$r = \max_{i,j}\left\{\max_i \sum_{j=1}^{n} u_{ij}, \max_j \sum_{i=1}^{n} u_{ij}\right\} \quad i,j \in \{1,2,3,\ldots,n\}$$

3.5. Step 5: Calculation of total relation fuzzy matrix

After generating normalized direct relation matrix, the fuzzy total-relation matrix can be calculated by using the formula which was introduced at the fifth step of the integrated method. The normalized matrix, the inverse, is first calculated, and subtracted from the matrix *I*, and the normalized matrix is later multiplied by the resulting matrix. Table 6 shows the total-relation fuzzy matrix.

Table 2
Critical factors affecting ship structural damage.

Code	Critical factors affecting ship structural damage
F1	Metal fatigue
F2	Corrosion
F3	Heavy weather
F4	Cargo stowage and operational plan
F5	Communication during cargo watch
F6	Synchronization of loading/unloading cargo and ballast operation
F7	Cargo handling equipment failure
F8	Ship's age, hull and structure condition
F9	Compatibility of international rules, regulations and guidelines about ship safety construction and cargo operation
F10	Quality of classification society that establishes and maintains technical standards for the construction and operation of ships
F11	Hull and structure status surveys of ship
F12	Ship shore safety checks before cargo operation and during cargo operation
F13	Competency of the ship and shore crew involved in the cargo handling operation
F14	Cargo handling systems familiarization of ship and shore crew
F15	Complying with the ship's planned maintenance system
F16	Cargo specification
F17	Passage planning include weather routing
F18	Approved cargo and hull stress monitoring system

Table 3
Linguistic assessment of the decision makers.

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18
F1	No	H	No	VL	No	No	H	VH	No	No	H	No	No	No	H	VL	VL	VL
F2	H	No	No	VL	No	No	H	VH	No	No	H	VL	No	No	H	VL	No	No
F3	H	L	No	L	VL	VL	L	H	VL	No	L	L	VL	VL	VL	No	L	VL
F4	VH	VL	No	No	L	H	L	H	VL	No	H	VH	VL	VL	VL	No	VL	L
F5	L	L	No	L	No	L	L	VL	VL	No	L	H	VL	VL	No	No	No	No
F6	H	L	No	H	No	No	L	L	VL	No	VL	L	No	VL	No	No	No	No
F7	VL	No	No	VH	VL	VH	No	VL	L	No	VL	L	No	VL	VL	No	No	No
F8	H	H	No	VL	No	VL	L	No	VH	H	VH	L	VL	No	VH	VL	VL	VL
F9	VH	VH	No	VH	L	L	H	VH	No	VH	VH	H	H	H	H	No	L	VH
F10	VL	VL	No	No	No	No	L	H	VH	No	VH	No	No	No	L	No	No	H
F11	VL	VL	No	L	No	L	H	VH	VH	VH	No	VL	VL	VL	H	No	VL	VL
F12	L	L	No	H	H	H	L	L	H	No	VL	No	No	VL	VL	No	No	VL
F13	L	L	No	VH	H	H	VL	H	H	No	L	H	No	H	H	No	H	No
F14	VL	VL	No	H	L	H	L	VL	L	No	VL	L	L	No	L	No	L	VL
F15	VH	VH	No	VL	No	No	H	VH	H	No	H	No	L	VL	No	No	VL	VL
F16	VH	VH	No	VH	VL	H	L	H	VL	No	VL	H	No	L	No	No	VL	L
F17	VH	L	VL	H	No	No	VL	H	VL	No	L	No	VL	VL	No	VL	No	No
F18	H	VL	No	H	VL	H	VL	H	L	VL	L	H	VL	H	VL	No	VL	No

Table 4
The direct relation fuzzy matrix.

	F1			F2			F3			…	F16			F17			F18		
F1	0.00	0.00	0.25	0.50	0.75	1.00	0.00	0.00	0.25	…	0.00	0.25	0.50	0.00	0.25	0.50	0.00	0.25	0.50
F2	0.50	0.75	1.00	0.00	0.00	0.25	0.00	0.00	0.25	…	0.00	0.25	0.50	0.00	0.00	0.25	0.00	0.00	0.25
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H17	0.75	1.00	1.00	0.25	0.50	0.75	0.00	0.25	0.50	…	0.00	0.25	0.50	0.00	0.00	0.25	0.00	0.00	0.25
H18	0.50	0.75	1.00	0.00	0.25	0.50	0.00	0.00	0.25	…	0.00	0.00	0.25	0.00	0.25	0.50	0.00	0.00	0.25

Table 5
The normalized fuzzy direct-relation matrix.

	F1			F2			F3			…	F16			F17			F18		
F1	0.00	0.00	0.02	0.03	0.05	0.07	0.00	0.00	0.02	…	0.00	0.02	0.03	0.00	0.02	0.03	0.00	0.02	0.03
F2	0.03	0.05	0.07	0.00	0.00	0.02	0.00	0.00	0.02	…	0.00	0.02	0.03	0.00	0.00	0.02	0.00	0.00	0.02
..	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
F17	0.05	0.07	0.07	0.02	0.03	0.05	0.00	0.02	0.03	…	0.00	0.02	0.03	0.00	0.00	0.02	0.00	0.00	0.02
H18	0.03	0.05	0.07	0.00	0.02	0.03	0.00	0.00	0.02	…	0.00	0.00	0.02	0.00	0.02	0.03	0.00	0.00	0.02

Table 6
The total-relation fuzzy matrix.

	F1			F2			F3			…	F16			F17			F18		
F1	0.01	0.03	0.15	0.04	0.07	0.19	0.00	0.00	0.07	…	0.00	0.02	0.09	0.00	0.03	0.11	0.00	0.03	0.12
F2	0.04	0.07	0.19	0.01	0.02	0.13	0.00	0.00	0.07	…	0.00	0.02	0.08	0.00	0.01	0.09	0.00	0.01	0.10
..	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
F17	0.06	0.09	0.20	0.02	0.06	0.17	0.00	0.02	0.09	…	0.00	0.02	0.09	0.00	0.01	0.09	0.00	0.01	0.10
H18	0.04	0.09	0.23	0.01	0.05	0.18	0.00	0.00	0.08	…	0.00	0.00	0.08	0.00	0.03	0.13	0.00	0.02	0.13

3.6. Step 6: Analysis of the model

At this step, the sum of each row and each column of $\widetilde{T}$ is calculated. The sum of rows and the sum of columns can be calculated as follows:

$$r_i = \sum_{j=1}^{n} T_{ij}$$

$$c_j = \sum_{i=1}^{n} T_{ij}$$

Then, the values of $\widetilde{r}_i+\widetilde{c}_j$ and $\widetilde{r}_i$- $\widetilde{c}_j$ can be calculated by $\widetilde{r}_i$and $\widetilde{c}_j$, where $\widetilde{r}_i+\widetilde{c}_j$ represent the degree of importance of factor i and $\widetilde{r}_i$- $\widetilde{c}_j$ represent net effects of factor i. Fuzzy scale of $\widetilde{r}_i$, $\widetilde{c}_j$, $\widetilde{r}_i+\widetilde{c}_j$ and $\widetilde{r}_i$-$\widetilde{c}_j$ is shown in Table 7.

3.7. Step 7: Defuzzification process

Defuzzification of $\widetilde{r}_i+\widetilde{c}_j$ and $\widetilde{r}_i$- $\widetilde{c}_j$ values was performed for converting the fuzzy numbers into crisp values at this step.

Through the defuzzification method, it is ensured that by translating from fuzzy values to exact values, the result can be checked and implemented. For this reason, thanks to the defuzzification process, it is possible for cluster elements to be comparable to each other. Various methods of defuzzification exist. The COA (Center of Area) technique used in this study was introduced by Ross (1995). The COA

Table 7
Fuzzy scale of $\tilde{r}_i$, $\tilde{c}_j$, $\tilde{r}_i$+$\tilde{c}_j$ and $\tilde{r}_i$-$\tilde{c}_j$

	$\tilde{r}_i$	$\tilde{c}_j$	$\tilde{r}_i + \tilde{c}_j$	$\tilde{r}_i - \tilde{c}_j$
F1	(0.32, 0.722, 2.477)	(0.593, 1.339, 3.574)	(0.913, 2.061, 6.051)	(-3.254, −0.618, 1.884)
F2	(0.253, 0.599, 2.288)	(0.434, 1.089, 3.192)	(0.687, 1.689, 5.48)	(-2.939, −0.49, 1.854)
F3	(0.158, 0.69, 2.559)	(0.052, 0.141, 1.434)	(0.21, 0.832, 3.992)	(-1.275, 0.549, 2.506)
F4	(0.334, 0.891, 2.907)	(0.671, 1.419, 3.671)	(1.005, 2.311, 6.579)	(-3.338, −0.528, 2.236)
F5	(0.175, 0.586, 2.35)	(0.16, 0.526, 2.224)	(0.336, 1.112, 4.574)	(-2.049, 0.06, 2.189)
F6	(0.18, 0.501, 2.166)	(0.407, 0.931, 2.985)	(0.587, 1.432, 5.151)	(-2.805, −0.43, 1.759)
F7	(0.183, 0.567, 2.188)	(0.451, 1.152, 3.566)	(0.634, 1.719, 5.754)	(-3.383, −0.586, 1.738)
F8	(0.41, 0.994, 2.941)	(0.631, 1.343, 3.606)	(1.041, 2.337, 6.548)	(-3.197, −0.349, 2.31)
F9	(0.792, 1.475, 3.793)	(0.345, 0.922, 2.908)	(1.137, 2.397, 6.702)	(-2.116, 0.553, 3.448)
F10	(0.301, 0.68, 2.364)	(0.178, 0.397, 1.878)	(0.479, 1.077, 4.242)	(-1.577, 0.283, 2.186)
F11	(0.348, 0.909, 2.891)	(0.519, 1.241, 3.47)	(0.867, 2.149, 6.361)	(-3.122, −0.332, 2.372)
F12	(0.278, 0.752, 2.68)	(0.481, 1.065, 3.167)	(0.759, 1.817, 5.847)	(-2.889, −0.314, 2.199)
F13	(0.505, 1.093, 3.314)	(0.089, 0.436, 2.038)	(0.593, 1.529, 5.352)	(-1.533, 0.657, 3.225)
F14	(0.251, 0.781, 2.747)	(0.144, 0.514, 2.172)	(0.394, 1.295, 4.919)	(-1.921, 0.267, 2.603)
F15	(0.381, 0.871, 2.725)	(0.313, 0.865, 2.816)	(0.694, 1.736, 5.541)	(-2.435, 0.006, 2.412)
F16	(0.4, 0.943, 2.837)	(0, 0.142, 1.433)	(0.4, 1.085, 4.27)	(-1.033, 0.801, 2.837)
F17	(0.208, 0.64, 2.386)	(0.099, 0.473, 2.116)	(0.306, 1.112, 4.502)	(-1.908, 0.167, 2.287)
F18	(0.322, 0.909, 3.006)	(0.232, 0.605, 2.368)	(0.554, 1.514, 5.375)	(-2.046, 0.304, 2.774)

defuzzification method is used to calculate BNP (Best Non-Fuzzy Performance) values (Ross, 1995). The equation introduced at the seventh step of the integrated method is used in order to estimate a convex fuzzy number $\tilde{\delta}$, and real number z* corresponding to its center of area (Akyuz and Celik, 2015).

3.8. Step 8: Obtaining final output and building up cause and effect relation diagram

The crisp values of the $\tilde{r}_i$, $\tilde{c}_j$, $\tilde{r}_i + \tilde{c}_j$ and $\tilde{r}_i$- $\tilde{c}_j$, provided in Table 8 as the final output, can be found to build up cause-effect relation diagram. In the last stage, cause and effect relationship diagram can be depicted based on the outcomes. The table below shows the final output.

Table 8
The final output.

Factors	r_i	c_j	r_i+c_j	r_i-c_j
F1	1.17	1.84	3.01	−0.66
F2	1.05	1.57	2.62	−0.52
F3	1.14	0.54	1.68	0.59
F4	1.38	1.92	3.30	−0.54
F5	1.04	0.97	2.01	0.07
F6	0.95	1.44	2.39	−0.49
F7	0.98	1.72	2.70	−0.74
F8	1.45	1.86	3.31	−0.41
F9	2.02	1.39	3.41	0.63
F10	1.11	0.82	1.93	0.30
F11	1.38	1.74	3.13	−0.36
F12	1.24	1.57	2.81	−0.33
F13	1.64	0.85	2.49	0.78
F14	1.26	0.94	2.20	0.32
F15	1.33	1.34	2.67	−0.01
F16	1.39	0.53	1.92	0.87
F17	1.08	0.90	1.97	0.18
F18	1.41	1.07	2.48	0.34

4. Results and discussion

The model of significant relations is shown in cause and effect diagram which was created according to Table 8. This model can be represented as a diagram in which the values of r_i+$c_j$are placed on the horizontal axis and the values of r_i-c_j on the vertical axis. The position and interaction of each factor with a point in the coordinates (r_i+c_j, r_i-c_j) are determined by coordinate system. Fig. 4 shows cause and effect diagram. According to the diagram, it may be necessary to divide the findings into two groups; cause and effect factors.

4.1. Cause factors

In order to evaluate factors affecting break-in-two accident of ships, it is crucial to focus on the cause factors that have positive value of r_i-c_j. F16, F13, F9, F3, F18, F14, F10, F17 and F5 are in cause group according to the cause-effect diagram. F16 (cargo specification) has the highest r_i-$c_j$value (0.87) among the all factors in cause group. This means that F16 has more impact on the entire process. Furthermore, F16 has high r_i value (1.39) among the causal factors from the point of influential impact degree. It shows that F16 has significant impact on the other factors. Thereafter, F13 (Competency of the ship and shore crew involved in the cargo handling operation) has the second highest r_i-$c_j$value (0.78) and is the second most important causal factor among all factors. F9 (Compatibility of international rules, regulations and guidelines about ship safety construction and cargo operation) has the highest degree of influential impact (Di) value which is 2.02. That's why it has great influence on the whole process. F9 is also the third most critical factor among the entire process because of its high r_i-$c_j$value (0.63). For this reason, F9 has significant impact on the entire break-in-two accident of ships. Similarly, F3 (Heavy weather) is another important factor among the whole process because the r_i-$c_j$value (0.59) is in the fourth place. Although F5 and F17 have the potential r_i values, their r_i-$c_j$values are the lowest among all factors. Therefore, they are not considered as critical factors.

4.2. Effect factors

F7, F1, F4, F2, F6, F8, F11, F12 and F15 have negative r_i-$c_j$values so these are effect factors. According to the cause-effect diagram, F4 (Cargo stowage and operational plan) and F8 (Ship's age, hull and structure condition) have the highest r_i+c_j value (3.30, 3.31) among the effect factors. Furthermore, degree of influenced impact index (c_j) values of F4 and F8 (1.92, 1.86) are high among the whole process. F11 and F1 also have the quite high r_i+$c_j$values (3.13 and 3.01) in the process. On the other hand, r_i-$c_j$values of F11 (Hull and structure status surveys of ship) and F1 (Metal fatigue) are very low (−0.36, −0.66). This means that F11 and F1 are easily affected from other factors. F15 (Complying with the ship's planned maintenance system) has the highest r_i-$c_j$value (−0.01) among the effect factor and has r_i+$c_j$value (2.67). This means that F15 is less effected factor among the whole process and has significant effect on the other factors.

The most critical factors that trigger break-in-two accident of ships were identified according to the cause-effect diagram. It is necessary to focus on these critical factors and to introduce preventive measures which obtained from experts who have enough knowledge and experience about ship structure and stability, cargo handling operation, hull strength, hull damage and materials used in shipbuilding. Table 9 shows preventive measures against the critical factors.

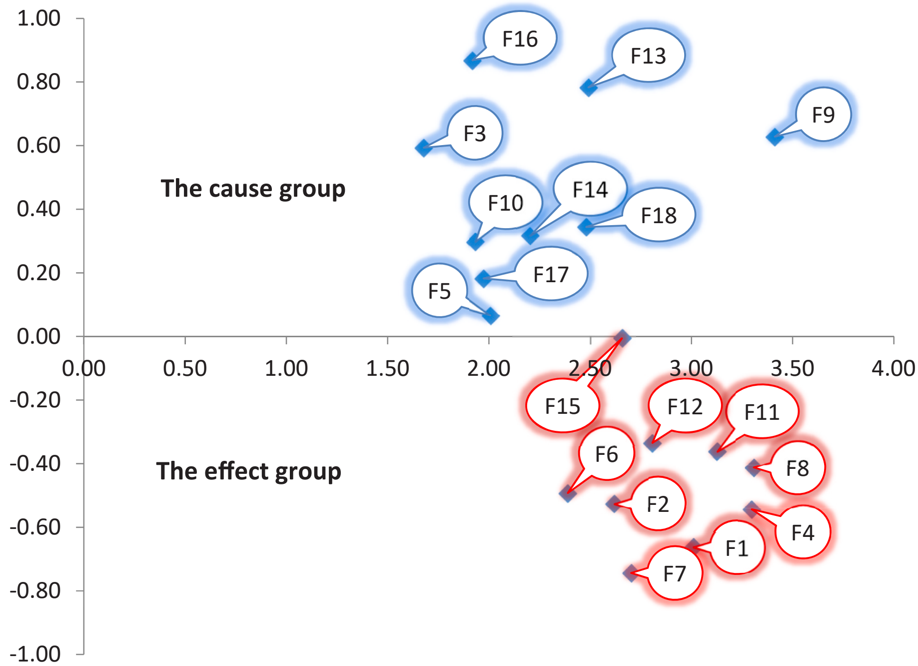

Fig. 4. Cause-effect diagram.

Table 9
Preventive measures.

Critical Factors	Preventive Measures
F3	Avoid heavy weather condition as much as possible in passage planning. Follow ship weather routing. Try to navigate taking big waves from port and starboard bow or quarter of ship. Take care of cargo lashing.
F4	Do not exceed the ship's SF and BM limits during cargo stowage and operational planning. Ensure that the loading/discharging operation and the ballast procedure are synchronized. Ensure that a continuous communication between ship and shore is established.
F8	Pay attention to the ship survey details, especially ship's thickness measurements. Ensure that the ship's crew fully complies with a well-organized maintenance system and does not neglect periodical checks of ship hull and structure. Prefer qualified and IACS member classification society for ship.
F9	Organize well-trained, qualified and experienced ship crew. Make sure that the ship management company follows up-to-date rules, regulations and guidelines about ship safety construction and cargo operation and ensures that they are applied on ships properly. Comply with the audit interval that defined by ship management company.
F13	Plan the recruitment process correctly. Organize periodic trainings for ship and shore crew involved in the cargo handling operation in accordance with their duty. Establish and apply detailed familiarization procedures for crew.
F15	Establish a well-designed planned maintenance system. Introduce a proper follow up procedure for ship's planned maintenance system. Adapt ship's crew to ship's planned maintenance system.
F16	Obtain all information about cargo specification. Determine all hazards of cargo for cargo handling and cargo transportation process and mitigate and control risks due to cargo specification. Plan safe cargo handling operation and cargo stowage according to cargo specification.

5. Conclusion

In this study, the main factors that trigger ship structural damage and break-in-two accident of ships were defined and the impact assessments of these factors were examined depending on the risk analysis. Unlike other studies in the literature, the Fuzzy DEMATEL method was used in this study and an alternative risk model that could be used for assessment of critical factors was created. Although studies on the analysis of ship structural damage such as age based crack assessment criteria, 3C and NASF in the literature show some results (Primorac and Parunov, 2016; Nair et al., 2017; Raju and Premanandh, 2018), it is striking that there is a lack of study on the factors that trigger break-in-two accident of ships. In this context, as a new approach, the causal relationships and weighting of the factors that trigger break-in-two accident of ships were analyzed. Analyzes revealed that critical factors have significant weights in the cause-effect diagram. As a result of the analysis, 18 factors that trigger break-in-two accident of ships were evaluated by considering the cause and effect group. Based on the evaluations of experts who have sufficient knowledge and experience about the structure and stability of the ship, cargo handling operation, hull strength, hull damage and materials used in shipbuilding, preventive measures were proposed to prevent break-in-two accidents of ships. Accordingly;

- Cargo specification (0.87), competency of the crew involved in the cargo handling operation (0.78), compatibility of international rules, regulations and guidelines about ship safety construction and cargo operation (0.63), heavy weather (0.59) were identified as the most critical factors among the cause group. Cargo handling operations, cargo stowage and cargo securing should be carried out according to the cargo specification considering material safety datasheet of the cargo to minimize the effect of cargo specification. A well-organized recruitment process should be applied to identify professionally competent employees. Detailed familiarization procedures and periodic in-service training standards should be established for ship/shore crew to ensure competent crew is involved in the cargo handling operation. In order to comply with the international rules, regulations and guidelines about ship safety construction and cargo operation, there should be a well-organized ship technical management system carried out by competent ship/shore crew who have sufficient experience in the profession. Proper passage planning should be applied taking care weather routing. All deck equipment and cargo lashing should be secured to minimize effects of heavy weather condition.

- Cargo stowage and operational plan (3.30), ship's age, hull and structure condition (3.31) and complying with the ship's planned maintenance system (2.67) were identified as the most critical factors among the effect group. In cargo stowage and operational plan, the synchronization of cargo and ballast handling operations should be ensured and SF and BM limits of the ship should not be exceeded. The hull and structure condition of a ship, directly related to the ship's age, should be surveyed at regular intervals by a member of high-quality classification society. Details of the ship's survey, especially the thickness measurements of the hull should be analyzed properly. The ship's crew should fully comply with the planned maintenance system and should not neglect periodical checks of hull and structure of the ship.

An alternative risk analysis approach was presented for the maritime industry to prevent break-in-two accident of ships. The results of this study can be used by decision makers such as ship class surveyors, ship/shore crews, loading masters, naval architecture and marine engineers to analyze and prevent possible ship structural damage and accidents. This study also revealed that the fuzzy DEMATEL approach can be used to analyze processes involving danger and cause-effect relationship in various sectors. Future studies can be developed using a multi-criteria decision-making method to take preventive measures against critical factors identified in this study. The study was limited to focusing on break-in-two accident, which is one type of structural accident of ships. Other types of ship structural accidents can also be analyzed using the same method.

CRediT authorship contribution statement

Ali Cem Kuzu: Conceptualization, Methodology, Data curation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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