Fuzzy DEMATEL Approach to Assess Factors Leading to Navigational Equipment Defect

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The increasing attention to the improvement and continuous enhancement of navigational safety has led to a high standard of navigation systems and the introduction of new technologies. Although several conventions, recommendations, guidelines, and performance standards for navigational equipment are set out by the International Maritime Organization (IMO), unexpected defects on this equipment may still occur on board. Any defect on this equipment may cause both accidents and commercial loss. This paper presented A fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique to assess factors that may cause navigational equipment defects, considering the academic and industrial gaps. Five homogeneous experts were asked to evaluate the relationship among the factors with respect to the linguistic scale. After the factors were ascertained and evaluated, preventive measures for most important factors were recommended in the view of experts' opinions in order to minimize and avoid their effect. The findings of the study will contribute to understanding the causes of navigational equipment defects and provide a basis for the continuous safety process of the ship's bridge operations in a comprehensive aspect.

KEY WORDS
~ Ship's navigation
~ Navigational equipment defect
~ Factor analysis
~ Fuzzy DEMATEL
~ Ship's bridge operations

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1. INTRODUCTION

Maritime transportation plays a vital role in the world economy and global trade. Over the last decade, the maritime industry has implemented several measures aiming to improve its safety level (Chauvin et al., 2013). Despite the automation in marine technology and the implementation of safety-related regulations, marine accidents are still the main concern for global maritime transportation (Xi et al., 2009). The International Maritime Organization (IMO) has focused on preventing vessel accidents by providing the minimum safety standards for ships and crews on board (Hong, 2015). According to the analysis of ship accidents obtained from the IMO, there are three main reasons that have caused accidents: equipment failure on ship itself, external environment (weather, oceanic condition, etc.) and human factor (Han et al., 2009). Although most of the accidents are caused by human factor (Baker et al., 2002; Erol and Basar, 2015; Luo et al., 2017), a considerable number of them occur due to technical or machinery problems (Han et al., 2009) such as engine breakdowns and equipment failure.

Due to a structural change in the industry and as a consequence of the introduction of new technologies, the design and operation of ships has evolved and continues to develop (Pomeroy and Jones, 2002). High standards of navigation are fundamental for the safety of vessels, crews, cargoes and for the protection of the environment (OCIMF, 2018). The ship navigation system is comprised of ship, navigation environment, and navigation technology (Han et al., 2009). The ship command is undoubtedly a complex, tough, challenging, and safety-critical task. Various interactive technologies and systems are used to assist the ship command that need to be designed with usability in mind in order to allow ease of use and not pose additional burdens to marine officers (Papachristos et al., 2012).

Commercial vessels are equipped with navigational equipment and tools such as gyro and magnetic compasses, ECDIS, automatic identification system (AIS), voyage data recorder (VDR), radars, speed and distance log devices, echo sounder, GPS receivers, etc. A considerable amount of literature has been published on navigational equipment, which may help to better understand its importance. AIS provides static and dynamic information of the vessels, such as the vessel's ID, name, width, length, type, and real manoeuvring behaviour of a vessel, such as longitude, latitude, heading, course, speed, draft, etc. It also transfers the sailing status information between vessels, and from vessels to shore or vice versa (Wu et al., 2020). Therefore, AIS data are an important source of information that facilitates decision-making in collision avoidance (Tsou, 2016). AIS data have been used in ship collision analysis, ship's behaviour detection, ship traffic characteristics, and ship emissions (Yan et al., 2020). The information availability from radar and Automatic Radar Plotting Aid (ARPA) forms the basis of several techniques that may assist in the safe navigation of vessels (Bole et al., 2013). Radar is the most important sensor for navigation or port management since it is capable of detecting vessels, waterfronts, and rocks actively (Ma et al., 2016). ARPA Radar system estimates variables such as the Closest Point of Approach (CPA) and Time to the Closest Point of Approach (TCPA) and includes software necessary to carry out a trial manoeuvre for a single target or group of targets (Ozoga and Montewka, 2018). ARPA Radar is widely used in the estimation of target optimization and collision risk (Ma et al., 2015; Chaturvedi, 2019; Stateczny, 2001; Xiaorui and Changchuan, 2011). The electronic chart display and information system (ECDIS) is another revolutionary new technology for modern navigation after ARPA and GPS (Tsou, 2016). ECDIS is a safety-relevant and software-based system with multiple options for display and integration, which is used to meet chart carriage requirements (Rutkowski, 2018). Much of the current literature on ECDIS pays particular attention to route planning, collision avoidance (Porathe et al., 2013; Tsou, 2016; Köckritz et al., 2016), performance analysis and development of ECDIS (Kastrisios and Pilikou, 2017; Žuškin et al., 2017; Wan et al., 2005), and training research (Legieć, 2016; Brčić et al., 2019). Gyro compass has become an indispensable instrument in almost all merchant ships or naval vessels due to its ability to detect the direction of true North. A great deal of previous research into gyro compass has focused on the ship's movement analysis (Pinheiro et al., 2016), heading estimation (Gade, 2016) and compass errors and calibration (Ackerman, 1965). Overall, these studies indicate the importance of navigational equipment. Although we have mentioned only certain items of navigational equipment in our literature review, the importance of others is also very obvious.

Any breakdown or defect of this equipment and tools may cause undesirable marine accidents, which can result in fatalities, injuries, cargo loss, pollution, etc. In addition, they may lead to commercial loss because of high repair costs or replacement of equipment, off-hire time due to restriction to port and channel entry, etc.

In this study, considering the importance of navigational equipment, common causes of equipment defects are discussed in detail. In this context, this paper aims to present a methodological approach to assess factors that may cause navigational equipment defects. To achieve this aim, the Fuzzy DEMATEL technique is used to identify and quantify the influence factors of navigation equipment defects. While some research has been carried out on both navigation equipment and the Fuzzy DEMATEL approach in the literature, there is no single study that focuses on the equipment defects. Therefore, this study will narrow the literature gap and also contribute to the maritime domain. This paper is composed of four themed chapters. A brief introduction and literature review regarding navigational equipment are given in this Chapter. Chapter 2 indicates methodologies used in the paper. The application of the proposed methodology and the results of analysis are shown in Chapter 3. The final Chapter provides a conclusion and the contribution of the study.

2. METHODOLOGICAL BACKGROUND

This study integrates the fuzzy sets and DEMATEL technique to assess factors that may cause navigational equipment defects. The fuzzy-DEMATEL model integrates the fuzzy linguistic aspect of the fuzzy theory with DEMATEL method (Wu and Lee, 2007). Applying DEMATEL in a fuzzy context allows examining the causal relationships of fuzzy variables and specifying the level of interactive influence among variables (Tsai et al., 2015).

Most research on Fuzzy Dematel has been carried out in the area of management and supply chain (Jassbi et al., 2011; Govindan et al, 2015; Acuña-Carvajal et al., 2019; Jeng, 2015; Tooranloo et al, 2017; Mirmousa and Dehnavi, 2016; Keskin, 2015). Also, numerous studies on Fuzzy Dematel have been carried out in different transportation systems such as land transportation (Baykasoğlu et al., 2013; Galehdar et al, 2018), aviation (Haghighat, 2017), maritime transportation (Mentes et al., 2015; Akyuz and Celik, 2015; Tac et al, 2020). Energy, construction, education, and tourism are the other industries in which Fuzzy Dematel studies were carried out (Muhammad and Cavus, 2017; Ocampo et al., 2018; Mangla et al., 2018; Mavi and Standing, 2018). Researchers mostly attempted to access critical factors and to evaluate relationships among the factors.

Methodologies of each method and integration of them are expressed in detail in the following section.

2.1. Fuzzy Sets

Various problems in system identification involve characteristics that are fundamentally non-probabilistic in nature (Zadeh, 1965). In response to this situation, Zadeh introduced the fuzzy set theory in 1965 as an alternative to probability theory (Höhle, 1996). The fuzzy set theory deals with linguistic variable problems in the real world (Gharakhani, 2012). Since its inception in 1965, the theory of fuzzy sets has advanced in a variety of ways and in many disciplines (Zimmermann, 2010). In fuzzy logic, fuzzy numbers are obtained by converting experts' linguistic statements. Triangular fuzzy numbers are shown as a triplet $\tilde{A} = (l,m,u)$ where l, m, and u points out lower, medium, and upper numbers of the fuzzy sets x≤y≤z). The membership function of a triangular fuzzy number can be illustrated as follows (Zadeh, 1965):

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

Figure 1 illustrates triangular fuzzy numbers, while Table 1 shows the relationship between the linguistic terms and triangular fuzzy numbers; Figure 2 demonstrates fuzzy rating and the function of membership in turn.

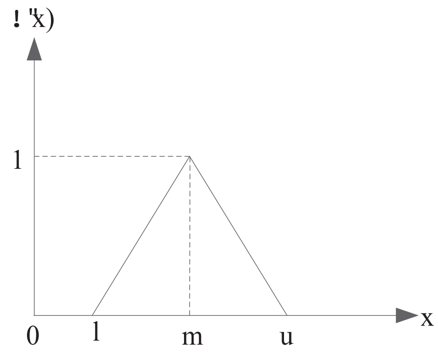

Figure 1.
Triangular fuzzy number.

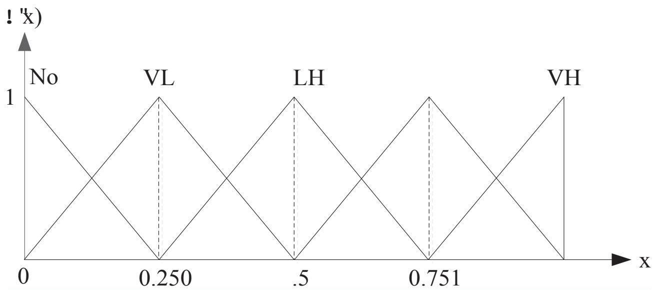

Figure 2.
Fuzzy rating and their membership function.

Table 1.
Relationship among linguistic terms and triangular 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 (H)	(0.5, 0.75, 1)
Very high influence (VH)	(0.75, 1, 1)

2.2. DEMATEL Technique

Gabus and Fontela (1972) define the DEMATEL method as one of the useful multi-criteria decision-making model generally used to negotiate complex and comprehensive decision-making problems. By visualization, the method aims to find out the cause and effect relationship among the criteria in terms of graph theory that permits analyzing and explaining the problem (Lin and Tzeng, 2009; Lin, 2013). The main steps of DEMATEL are defined as follows (Celik and Akyuz, 2015):

Step 1: Define critical and effective factors of the problem by expert opinion, literature review, or brainstorming. Identify the evaluation criteria and lay out the fuzzy linguistic scale for experts' pairwise evaluation. Establish the direct relation matrix when real values are obtained by converting experts' linguistic assessments.

A = [a_{ij}], where A is a nxn non-negative matrix, a_{ij} states the direct impact of factor i on factor j; and when i = j, the diagonal elements a_{ij} = 0.

Step 2: Figure out a normalized direct relation matrix D = [d_{ij}], by using the equations below:

$$s=\frac{1}{\max_{1\le i\le n}\sum_{j=1}^{n}a_{ij}}\; i,j=1,2,\ldots,n. \tag{2}$$

$$D=s.A \tag{3}$$

Step 3: Acquire a total-relation matrix (T) by use of Equation (4). I represents nxn identity matrix.

$$T=D\,(I-D)^{-1} \tag{4}$$

Step 4: Calculate the sum of the rows and columns of matrix T. r_i and c_j are determined through the following Equations 5 and 6 respectively. While r_i states all the direct and indirect influence given by the criterion i to all the other factors (Eq. 5), c_j provides the degree of the influenced impact (Eq. 6).

$$r_i=\sum_{1\le j\le n}t_{ij} \tag{5}$$

$$c_j=\sum_{1\le i\le n}t_{ij} \tag{6}$$

Step 5: Finally, figure the cause and effect relationship diagram with reference to the $r_i + c_j$ and $r_i - c_j$.

2.3. Fuzzy DEMATEL

Integration of fuzzy sets and DEMATEL method are expressed step by step (Akyuz and Celik, 2015; Tsai et al., 2015).

Step 1 - Consult the experts whose judgments are reliable due to their knowledge, skill, and experience.

Step 2 - Determine factors and construct fuzzy scale: critical factors are specified to carry out evaluation. Afterwards, linguistic variable is used in accordance with the five fuzzy scales (no influence, very low influence, low influence, high influence, and very high influence), and the corresponding triangular fuzzy members are determined.

Step 3 - Obtain evaluation of the group decision-makers: the pairwise comparison is built by using linguistic variables. Then, fuzzy assessments are transformed into defuzzified and aggregated as a crisp value. Eventually, initial direct-relation fuzzy matrix Ē is established by using the following equations respectively.

$$\bar{E}=\begin{bmatrix} 0 & \cdots & \bar{E}_{1n} \\ \vdots & \ddots & \vdots \\ \bar{E}_{1n} & \cdots & 0 \end{bmatrix} \tag{7}$$

$$\bar{e}_{ij}=(l_{ij},m_{ij},u_{ij}) \tag{8}$$

Step 4 - Construct a normalized direct-relation fuzzy matrix: this matrix is built by using the following equations where β_i and γ stand for triangular fuzzy numbers.

$$\beta_i=\sum\bar{e}_{ij}=(\sum_{j=1}^{n}l_{ij},\sum_{j=1}^{n}m_{ij},\sum_{j=1}^{n}u_{ij}) \tag{9}$$

$$y=\max(\sum_{j=1}^{n}u_{ij}) \tag{10}$$

Then, linear scale transformation is implemented to convert the factors into comparable scales. The normalized direct-relation fuzzy matrix F of experts is calculated as follows:

$$F=\begin{bmatrix} F_{11} & \cdots & F_{1n} \\ \vdots & \ddots & \vdots \\ F_{1n} & \cdots & F_{nn} \end{bmatrix} \tag{11}$$

where $f_{ij}=\frac{e_{ij}}{\gamma}=(\frac{e_{ij}}{\gamma},\frac{e_{ij}}{\gamma},\frac{e_{ij}}{\gamma})$

Step 5 - Calculate total-relation fuzzy matrix: this matrix is calculated on the basis of $\lim_{\omega \to \infty} F^{\omega} = 0$. The crisp case of the total-relation fuzzy matrix is explained in detail as follows:

$$T = \lim_{\omega \to \infty} (F + F^2 + ... + F^{\omega}) \quad (12)$$

$$T = \begin{bmatrix} t_{11} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{1n} & \cdots & t_{nn} \end{bmatrix} \quad (13)$$

where $t_{ij} = (l_{ij}'', m_{ij}'', u_{ij}'')$

$$Matrix\,[l_{ij}''] = F_l \, x \, (I - F_l)^{-1} \quad (14)$$

$$Matrix\,[m_{ij}''] = F_m \, x \, (I - F_m)^{-1} \quad (15)$$

$$Matrix\,[u_{ij}''] = F_u \, x \, (I - F_u)^{-1} \quad (16)$$

Step 6 - Analyze the structural model: figure out $r_i + c_j$ and $r_i - c_j$ after calculating matrix T. Since $r_i + c_j$ presents the importance of factor i, $r_i - c_j$ states the net effect of factor i.

Step 7 – Defuzzify $r_i + c_j$ and $r_i - c_j$: defuzzify $r_i + c_j$ + and $r_i - c_j$ by accepting the COA (center of area) defuzzification method proposed by Ross (1995). For a convex fuzzy number δ, a real number z* corresponding to its center of area can be estimated with the following Equation 17 (Akyuz and Celik, 2015).

$$z^* = \frac{\int \mu_{\delta}(z)\, z dz}{\int \mu_{\delta}(z)\, dz} \quad (17)$$

The BNP value of a fuzzy number $G = (l_{ij}, m_{ij}, u_{ij})$ is evaluated by means of the following Equation 18.

$$BNP_{ij} = \frac{u_{ij} - l_{ij} + m_{ij} - l_{ij}}{3} + l_{ij} \quad (18)$$

Step 8- Build up cause-effect relation diagram: in the last step, the cause and effect relation diagram is depicted by mapping the dataset of $r_i + c_j$ and $r_i - c_j$. The calculation can be done according to Step 6.

3. APPLICATION

In this section, the Fuzzy DEMATEL technique is used to identify and quantify the influence factors of navigation equipment defect.

3.1. Problem Statement

Since 1959, the International Maritime Organization (IMO) has been set to improve navigational safety by introducing conventions, recommendations and other instruments including both guidelines on navigational issues and performance standards for navigational and communication equipment (IMO, 2020). As per SOLAS Chapter V, navigational systems and equipment must meet the IMO standards and must be approved by the administration to be installed on the bridge, and all these aids must be checked from time to time for their performance and accuracy (SOLAS, 2018). Although all periodic checks on navigational equipment should be conducted and Officers should be familiar with the vessel's equipment and testing requirements, unexpected defects on navigational equipment may still occur on board.

In this study, factors that may cause defects on navigational equipment are analyzed. Then, a detailed survey was carried out with 5 homogeneous experts who work in reputable marine electronics and communication companies that provide services for navigation equipment defects. They all work as service engineers, all have more than 5 years of experience and have performed several navigation equipment defect services. The survey was sent to the experts via e-mail in MS Word format. A detailed explanation of the survey, such as the aim, where the results will be used, how to do pair-wise comparison, etc., was given in the cover letter. The expert judgments' arithmetic means were obtained. Table 2 shows common causes of navigational equipment defect.

Table 2.
Common factors of navigational equipment defect.

Code	Factor
F1	Wear and Tear (i.e., loss of electrical properties of electronic components based on time, freezing of electrical equipment units such as capacitors based on time)
F2	Leakage of electricity
F3	Insufficient grounding
F4	Exposure to dust and fouling
F5	Overheating and airless equipment
F6	Vibrations of vessel
F7	Severe weather conditions (i.e., thunderbolt)
F8	Use of poor-quality spare parts
F9	Use of USB flash drives, cables and other external sources which may carry viruses
F10	Technician's error and negligence (i.e., bad installation)
F11	Not carrying out equipment service on time
F12	Breakdowns in operating procedures
F13	Unfamiliarity of officers with equipment
F14	Not tracking and rectifying failure alarms on time

3.2. Analysis of Respondents - Empirical Analysis

A comprehensive survey was performed with five experts. The experts evaluated the relationship among the factors that may cause defect on navigational equipment with respect to the linguistic scale presented in Table 1. Then, the arithmetic means of their judgements were obtained. Accordingly, Table 3 shows linguistic assessments of the five experts.

Table 3.
Linguistic assessments of marine experts.

	F1	F2	F3	…..	F13	F14
F1	NO, NO, NO, NO, NO	VH, VH, VH, VH, VH	VH, VL, VH, VH, H	……	VH, VL, VH, L, H	VH, NO, VH, VH, H
F2	VH, H, VH, H, VH	NO, NO, NO, NO, NO	VH, VL, VH, L, NO	……	H, VL, H, NO, L	H, NO, H, VH, H
F3	VH, H, VH, H, H	VH, VL, VH, H, VH	NO, NO, NO, NO, NO	……	VL, VL, VL, NO, NO	VL, NO, VL, VL, NO
F4	VH, VH, VH, H, H	H, VL, H, L, L	VL, VL, VL, VL, NO	……	VL, L, VL, NO, NO	NO, NO, NO, NO, NO
F5	L, VH, L, H, H	NO, L, NO, L, VH	H, VL, H, VL, NO	……	H, NO, H, NO, NO	H, NO, H, NO, NO
F6	NO, H, NO, VL, NO	H, L, H, VL, NO	VL, VL, VL, VL, NO	……	NO, NO, NO, NO, NO	NO, NO, NO, NO, NO
F7	H, H, H, L, NO	H, L, H, VL, H	H, L, H, L, NO	……	NO, NO, NO, VL, NO	NO, NO, NO, L, NO
F8	VH, VH, VH, VH, VH	VH, H, VH, H, VH	H, H, H, VH, NO	……	NO, VL, NO, NO, NO	NO, VL, NO, NO, NO
F9	NO, VL, NO, H, L	NO, VL, NO, VL, NO	NO, NO, NO, NO, L	……	VH, VL, VH, L, NO	VH, NO, VH, VH, NO
F10	H, VH, H, VH, NO	L, VH, L, VH, VH	VH, VH, VH, VH, NO	……	NO, VL, NO, VL, NO	NO, H, NO, NO, NO
F11	H, H, H, VH, VH	VL, L, VL, VH, H	VL, VL, VL, VH, NO	……	NO, VL, NO, NO, NO	NO, VL, NO, VL, NO
F12	H, VL, H, VL, NO	VL, NO, VL, VL, H	VL, NO, VL, NO, L	……	VH, VL, VH, VH, VH	VH, H, VH, VH, VH
F13	NO, L, NO, H, NO	H, VL, H, H, NO	VL, VL, VL, H, NO	……	NO, NO, NO, NO, NO	VH, VH, VH, VH, NO
F14	VH, H, VH, L, L	H, VL, H, NO, H	VL, VL, VL, NO, NO	……	VH, L, VH, L, NO	NO, NO, NO, NO, NO

Firstly, an initial direct-relation fuzzy matrix, figured in Table 4, was constructed as per the experts' evaluation. Secondly, a normalized direct-relation fuzzy matrix shown in Table 5 was figured out by means of Equations 13-15. Thirdly, a total-relation fuzzy matrix was calculated by means of Equations 16-20 provided in Table 6.

Table 4.
Initial direct-relation fuzzy matrix.

	F1	F2	F3	…	F13	F14
F1	(0, 0, 0.25)	(0.75, 1, 1)	(0.55, 0.8, 0.9)	…	(0.45, 0.7, 0.85)	(0.55, 0.75, 0.85)
F2	(0.65, 0.9, 1)	(0, 0, 0,25)	(0.35, 0.55, 0.7)	…	(0.25, 0.45, 0.7)	(0.45, 0.65, 0.85)
F3	(0.6, 0.85,1)	(0,55 0,8, 0.9)	(0, 0, 0,25)	…	(0, 0.15, 0.4)	(0, 0.15, 0.4)
⋮	⋮	⋮	⋮	⋮	⋮	⋮
F13	(0.15, 0.25, 0.5)	(0.3, 0.5, 0.75)	(0.1, 0.3, 0.55)	…	(0, 0, 0.25)	(0.6, 0.8, 0.85)
F14	(0.5, 0.75, 0.9)	(0.3, 0.5, 0.75)	(0, 0.15, 0.4)	…	(0.4, 0.6, 0.75)	(0, 0, 0.25)

Table 5.
Normalized direct-relation fuzzy matrix.

	F1	F2	F3	…	F13	F14
F1	(0, 0, 0.02)	(0.07, 0.09, 0.09)	(0.05, 0.07, 0.08)	…	(0.04, 0.06, 0.08)	(0.05, 0.07, 0.08)
F2	(0.06, 0.08, 0.09)	(0, 0, 0.02)	(0.03, 0.05, 0.06)	…	(0.02, 0.04, 0.06)	(0.04, 0.06, 0.08)
F3	(0.06, 0.08, 0.09)	(0.05, 0.07, 0.08)	(0, 0, 0.02)	…	(0, 0.01, 0.04)	(0, 0.01, 0.04)
⋮	⋮	⋮	⋮	⋮	⋮	⋮
F13	(0.01, 0.02, 0.05)	(0.03, 0.05, 0.07)	(0.01, 0.03, 0.05)	…	(0, 0, 0.02)	(0.06, 0.07, 0.08)
F14	(0.05, 0.07, 0.08)	(0.03, 0.05, 0.07)	(0, 0.01, 0.04)	…	(0.04, 0.06, 0.07)	(0, 0, 0.02)

Table 6.
Total-relation fuzzy matrix.

	F1	F2	F3	…	F13	F14
F1	(0.03, 0.08, 0.27)	(0.09, 0.15, 0.32)	(0.06, 0.12, 0.27)	…	(0.05, 0.10, 0.24)	(0.06, 0.11, 0.25)
F2	(0.07, 0.13, 0.29)	(0.02, 0.05, 0.21)	(0.04, 0.08, 0.22)	…	(0.03, 0.07, 0.20)	(0.05, 0.09, 0.22)
F3	(0.07, 0.12, 0.28)	(0.06, 0.11, 0.26)	(0.01, 0.04, 0.17)	…	(0.01, 0.04, 0.17)	(0.01, 0.04, 0.17)
⋮	⋮	⋮	⋮	⋮	⋮	⋮
F13	(0.03, 0.07, 0.24)	(0.04, 0.08, 0.25)	(0.01, 0.05, 0.20)	…	(0.01, 0.03, 0.16)	(0.07, 0.11, 0.22)
F14	(0.06, 0.11, 0.26)	(0.04, 0.08, 0.23)	(0.01, 0.04, 0.17)	…	(0.05, 0.08, 0.19)	(0.01, 0.03, 0.15)

The fuzzy values of r_i, c_j, $r_i + c_j$, $r_i - c_j$ shown in Table 7 were calculated using total-relation matrix. Afterwards, defuzzification process was carried out to convert the fuzzy numbers into crisp values. The crisp values of r_i, c_j, $r_i + c_j$, $r_i - c_j$ shown in Table 8 enabled to provide the cause and effect relation.

Table 7.
Fuzzy values of $r_i, c_j, r_i + c_j, r_i - c_j$.

	r_i	c_j	$r_i + c_j$	$r_i - c_j$
F1	(0.64, 1.26, 3.38)	(0.59, 1.37, 3.57)	(1.23, 2.64, 6.96)	(-2.93, -0.11, 2.79)
F2	(0.43, 0.91, 2.80)	(0.68, 1.24, 3.34)	(1.11, 2.14, 6.14)	(-2.91, -0.33, 2.14)
F3	(0.35, 0.82, 2.62)	(0.37, 0.89, 2.73)	(0.72, 1.71, 5.35)	(-2.38, -0.07, 2.26)
...	...	...	...	...
F13	(0.42, 0.87, 2.71)	(0.31, 0.73, 2.42)	(0.73, 1.60, 5.13)	(-2.00, 0.14, 2.40)
F14	(0.34, 0.73, 2.45)	(0.41, 0.82, 2.52)	(0.76, 1.56, 4.97)	(-2.18, -0.09, 2.04)

Table 8.
Crisp values of $r_i, c_j, r_i + c_j, r_i - c_j$.

	r_i	c_j	$r_i + c_j$	$r_i - c_j$
F1	1,76	1,85	3,61	-0,08
F2	1,38	1,75	3,13	-0,37
F3	1,26	1,33	2,59	-0,06
F4	1,12	1,22	2,34	-0,09
F5	1,21	1,56	2,77	-0,35
F6	0,90	0,90	1,79	0,00
F7	1,17	0,85	2,02	0,32
F8	1,43	1,09	2,52	0,35
F9	0,81	0,89	1,70	-0,07
F10	1,57	1,20	2,77	0,37
F11	1,20	0,95	2,16	0,25
F12	1,12	1,47	2,59	-0,34
F13	1,33	1,15	2,49	0,18
F14	1,18	1,25	2,43	-0,08

3.3. Findings and Discussion

Factors that cause navigational equipment defects can be divided into two significant groups: cause and effect factors. According to the results presented in $r_i, c_j, r_i + c_j, r_i - c_j$ Table 8, the cause-effect relation diagram is shown in Figure 3.

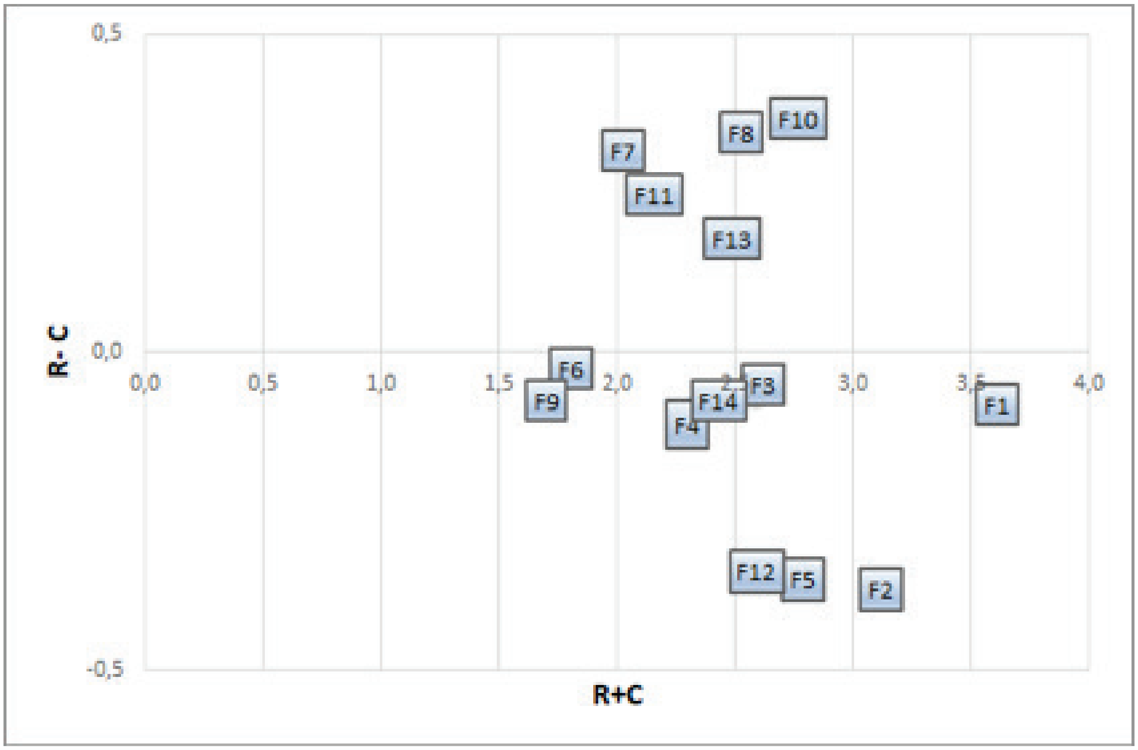

Figure 3.
Cause-effect relation diagram.

3.3.1. Cause Factors

To prevent navigational equipment defects, it is very important to focus on the cause factors. r_i - c_j value helps to find significant causal factors that may result in navigational equipment defects. According to Table 8, F10 (Technician error and negligence) has the highest r_i - c_j value of all the factors, which means that it has an important impact. At the same time, F10 has quite a high r_i value when compared to the other factors. It shows that F10 has a considerable impact on the other factors. Having the second highest r_i - c_j value, F8 (Use of poor quality spare parts) is the second most important cause factor. F8 also has quite a high r_i value. Similarly, F7 (Severe weather conditions) is an important cause factor since it ranks third among all the factors.

3.3.2. Effect Factors

Effect factors, which are quickly and easily affected by other factors, can cause a major malfunction considering navigation equipment working process. According to Table 8, F1 (Wear and Tear) has the highest r_i + c_j value of all the factors. Also, it has the highest degree of influential impact index (i) and influential impact index (c_j) values. In short, F1 has a possible effect that leads to navigational equipment failure. Similarly, F2 (Leakage of electricity) has the second-highest r_i + c_j value. As it can be seen, the c_j and r_i values of F2 are quite high compared with other factors. Another important effect factor that leads to navigational equipment failures is F5 (Overheating and airless equipment) since it has the third-highest r_i + c_j value.

3.4. Preventive Measures Proposal

According to the study results, F10, F8, F7, F1, F2, and F5 are the most important factors that may lead to navigational equipment defects. The experts with a wide experience and knowledge proposed preventive measures against these factors, which are provided in Table 9.

Table 9.
Preventive measures.

Factor No	Factors	Suggested preventive actions
F10	Technician's error and negligence	Contracting only competent and certified technicians by the manufacturer.
F8	Use of poor-quality spare parts	Purchasing only genuine spare part by the manufacturer and/or official distribution by the manufacturer.
F7	Severe weather conditions	Installation of equipment /material that is non-corrosive. Checking and verifying connections after installation. Sufficient isolation/covering of equipment.
F1	Wear and tear	Including manufacturer's recommended regular inspection/check/ maintenance of the PMS system. Maintaining minimum spare parts on board recommended by the manufacturer.
F2	Leakage of electricity	Including regular Megger test as recommended by the manufacturer of the PMS system.
F5	Overheating and airless equipment	Adequate cooling system to be provided by the manufacturer. Vessel is to maintain ambient temperature as recommended by the manufacturer. Vessel manager provides guidelines for the ship's staff regarding precautions during excessive heat and cold.

4. CONCLUSION

A high-standard navigation system is an essential requirement for the safety of the ship, human life, protection of cargo and the environment. Although there are a number of conventions, recommendations, guidelines and standards for navigational and communication equipment laid down by the International Maritime Organization (IMO) in order to improve navigational safety, unexpected defects on navigational equipment may still occur on board. To date, several studies have attempted to explain the importance of navigational equipment; however, none focused on the equipment defects. This paper presented the Fuzzy DEMATEL technique to assess factors that may cause navigational equipment defects, considering the academic and industrial gap. Application of DEMATEL in a fuzzy context allowed examining the causal relationships of fuzzy variables and specifying the level of interactive influence among the variables. Thus, factors leading to navigational equipment failures were identified and evaluated in association with visual cause-effect relation diagram. The main findings of this study show that Technician error and negligence (F10), Use of poor-quality spare parts (F8), Severe weather conditions (F7), Wear and Tear (F1), Leakage of electricity (F2), and Overheating and airless equipment (F5) are the most remarkable factors that cause navigational equipment failures since F10, F8, and F7 are the cause factors, and F1, F2, and F5 are the effect factors. In this way, factors that may cause navigational equipment defects are ascertained. Then, preventive measures are recommended by the experts' in order to minimize and avoid the effect of factors. These findings contribute in several ways to understanding of the causes of navigational equipment defects and provide the basis for a continuous safety process of the ship's bridge operations from a comprehensive aspect. Further research could also be conducted to determine the cause-effect factors of other shipboard operation equipment, such as cargo handling equipment, maneuvering equipment, etc., which would develop better understanding of the ship's safety.

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CONFLICT OF INTEREST

I wish to confirm that there are no potential conflicts of interest associated with this study.

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