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The effect of nonconformities encountered in the use of technology on the occurrence of collision, contact and grounding accidents

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ABSTRACT

Technology and its innovative applications make life easier and reduce the workload on seafarers. Today's ship bridges have much more modern and integrated navigation systems than before, and the ship's handling and management have become much easier. However, nonconformities encountered in the use of technological devices may cause accidents. In this study, the effect of human factor related errors associated with the use of the bridge's electronic navigational devices on grounding and collision-contact accidents was investigated. Nonconformities obtained from 175 collision-contact and 115 grounding accident reports were qualitatively analysed by means of human factor analysis and a classification system. Afterwards, relationships between nonconformities and their probabilities were evaluated quantitatively via a Bayesian network method. As a result of the study, the accident network was revealed. This accident network summarizes how operating errors in the use of technological equipment cause accidents. Recommendations on the prevention of accidents caused by operating errors associated with the use of new technologies are finally given.

1. Introduction

To ensure sustainable trade, a safe environment must be created for vessels at sea [80]. The International Maritime Organization (IMO) was established in 1958 to maintain maritime safety. Although this organization introduces new regulations, training forms, and the use of new ship equipment, accidents continue to occur [72]. Today, marine accidents remain a major concern, both environmentally and economically [89]. Spatial constraints, heavy weather and sea conditions, malfunctions and human error are the dominant factors in the occurrence of accidents [18, 23, 82]. Human error accounts for 75-96% of losses in marine operations. Although human error does not always result in a disaster, it can cause significant economic losses due to delayed operations [69].

Undoubtedly, advances in navigation aid systems from past to present have played an essential role in reducing human error [24]. However, technological advances have posed new risks and potential accident scenarios [19, 28, 61]. It is obvious that considerations related to human judgment will remain at the forefront of this industry until the management of maritime transport transitions to autonomous systems and software [49, 52]. In the past, the interactions between operators and technology have caused major disasters [16]. To prevent such disasters in the maritime industry, it is important to understand the perception, abilities, decisions, and effects of watchkeeping officers on developing automation systems and their effects on the likelihood of accidents [59]. Recent studies show that new accident-related factors are coming to the forefront: Errors in the use of electronic navigation devices, overconfidence in data presented by automation control systems, lack of understanding of the natural weaknesses of electronic navigation devices, ergonomic design failure, and human-computer interfaces are some of them [9, 31, 58]. Moreover, the complex structure of automation systems and the incomplete or erroneous steps taken by officers who have not mastered this structure can cause devastating accidents [46]. When these factors are taken into consideration, it becomes obvious that human-based errors in relation to electronic navigation systems should be identified and evaluated to prevent future accidents.

"Collision-contact" and "Grounding" are among the most common accident categories [53]. According to Swedish Club [71] the average cost of these accidents per ship is greater than 800,000 USD. Collision-contact and grounding also account for approximately half of the boat and machine damage costs incurred due to accidents on ships.

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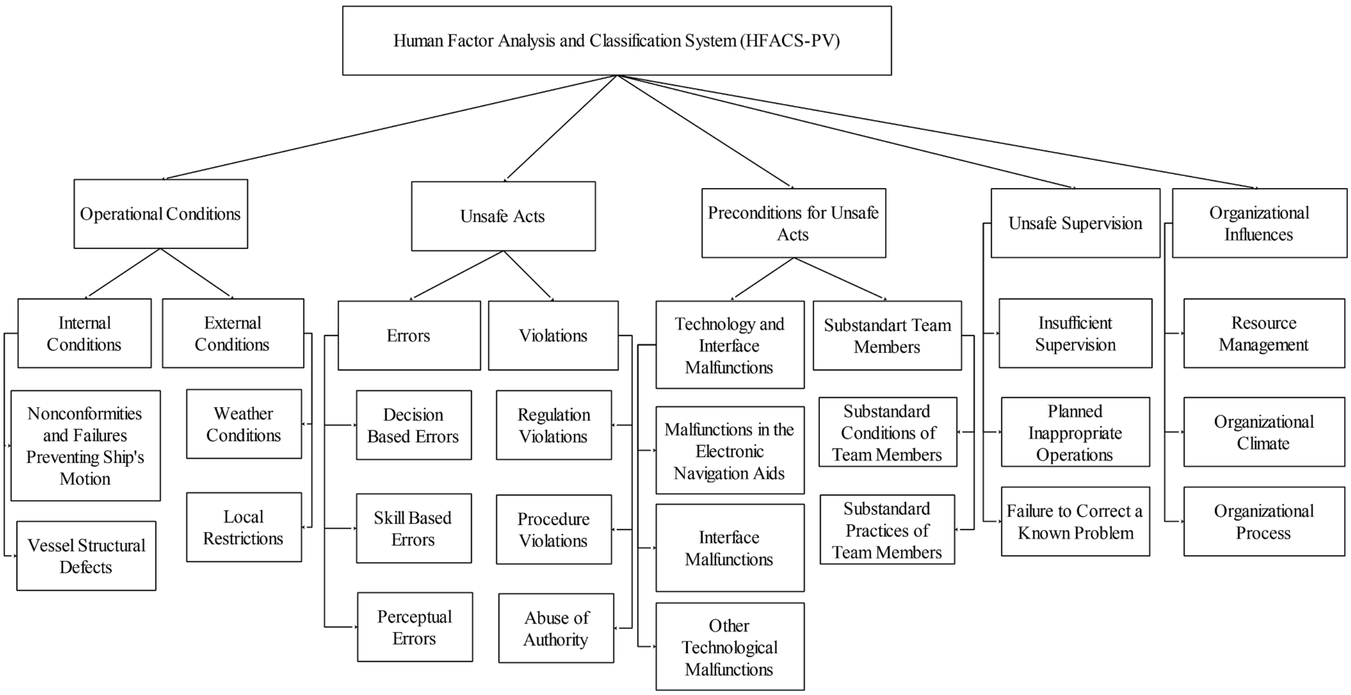


Figure 1. Human factor analysis and classification system (HFACS-PV)

Therefore, preventing collision-contact and grounding accidents will provide significant savings for all sides of the transport industry.

Accident analysis studies are carried out to determine the factors that trigger accidents and their severity. Thus, accident prevention strategies are identified and implemented. Then, the effects of these strategies on accidents are observed [70]. Achieving effective results from accident analysis depends on identifying the causes of the accident and the correct definition of the relationship between them. Accident analysis models make it possible to determine the effects of accident causes [37]. Therefore, today there are nearly 100 accident analysis models whose applicability is proven by at least one case study [32, 40, 81]. Accident investigators have to choose the most appropriate method. It would be appropriate to select the method according to the complexity of the accident and the elements to be analysed [81]. With the Human Factors Analysis and Classification System (HFACS) based on Reason's Swiss Cheese model, it is possible to systematically examine the effects of human factors on accidents and classify the causes of accidents [67]. However, HFACS does not explain the relationship between causes. At this stage, a Bayesian network method is used. Bayesian network is a method based on conditional probability that makes it possible to interpret the relationship between causes by means of nodes and edges. Thus, users can estimate the risk of accident due to varying conditions [10, 54, 66].

In this study, the effects of operational errors associated with the use of new technologies in maritime transport on collision-contact and grounding accidents were examined via a hybrid method of a HFACS and a Bayesian network. The HFACS method was used to categorize the causes of accidents according to a hierarchical structure. The Bayesian network method was implemented to show the relationships between accident causes. Using the network structure presented in this study, it is possible to detect the nonconformities that play a role in the occurrence of accidents and analyse the impact of an accident. The risk of accident occurrence under variable conditions can be estimated using the network structure. Thus, it is possible to predict the effect of measures that can be taken to prevent accidents on ships.

2. Background

2.1. The HFACS

The HFACS is a human factor analysis system that categorizes the impact of human errors on accident formation according to a hierarchical structure. Using this method, it is possible to systematically examine the effects of human-related factors on accidents and elaborate on the relevant causes and sub-causes. The most important feature that distinguishes the HFACS from other accident analysis methods is the ability to demonstrate the role of administrative and organizational factors in complex systems [83]. The HFACS method does not require expert opinions on the classification of accident causes or causal factors. For this reason, researchers who have mastered the main structure and sub-structure can show the occurrence of accidents gradually [77].

Over time, as the recognition and application area of this method expanded, the HFACS was transformed by many researchers from various sectors [14, 15]. It has a wide range of applications in air transport [14, 68, 84], maritime transport [12], railway transport [5], the mining industry [41, 57], the oil and gas industry [73], and many other sectors. The last change in the HFACS structure concerning maritime transport was made by Uğurlu *et al.* [77], who proved the validity of the HFACS-PV (Human Factor Analysis and Classification System for Passenger Vessel) structure through three case studies [[65, 78,88]. They added a level of operational conditions (environmental factors) to the main structure and made minor changes to the other levels, making them compatible with the maritime sector. The HFACS-PV structure consists of 5 levels, unlike the original HFACS structure. Figure 1 shows the HFACS-PV's main structure and sub-structures. In this study, accident analyses were performed using the HFACS-PV framework.

2.2. Bayesian Network

A Bayesian network is a network cycle in which variables are represented by nodes' and inter-nodes' relations with each other (probabilistic dependency), which are shown using edges [39, 45]. In this type of network structure, nodes (inputs) are factors that contribute to the

Table 1
Distribution of accident data according to databases

Database Name	Accident category Grounding (No.)	Collision-contact (No.)	Total	Accidents relating to the use of bridge-navigation equipment Grounding (No.)	Collision-contact (No.)	Total
MAIB	59	83	142	36	55	91
ATSB	33	28	61	21	19	40
JTSB	4	24	28	2	20	22
TSB	35	25	60	21	8	29
NTSB	6	33	39	2	13	15
EMSA	35	68	103	25	39	64
MARDEP	1	14	15	1	13	14
BMA	7	5	12	5	2	7
KAIK	5	8	13	2	6	8
Total	185	286	471	115	175	290

main problem (output) [62]. There are no restrictions on the number of children or parents that nodes can have [25]. In contrast to regression and similar methods, the Bayesian network method does not depend on a single output variable and can be deduced for all variables in the network. These features make it an effective tool for decision-making and analysis [91]. Therefore, the Bayesian network method has been used as a method in medical diagnosis [10], marketing [66], earthquake risk assessment [54] and accident analysis [92, 94].

In this type of network structure, probability values and conditional probability tables are created depending on the inputs. There are two main approaches to calculating the probability values of nodes in a Bayesian network structure. One of them involves statistical data, and the other involves expert judgement. If sufficient statistical data is not available for the examined events, conditional probability tables are formed based on expert opinions [50,60,67]. Conditional probability tables explain the effects of nodes on each other independently or dependently [30, 33]. A Bayesian network includes two types of approaches: qualitative and quantitative [42]. In the qualitative approach, the variables of the network and the relationships between them are transferred graphically. In the quantitative approach, the probabilistic relationships between the variables (conditional probability tables) are established. A Bayesian network based on data was formulated in this study, and conditional probability tables were constructed.

Nodes that do not have a dependency or have no parents, have marginalised probabilities [30, 33]. Marginalised probability is the unconditional probability of an event. The marginalised probability of an event A, denoted by P(A), is the probability that event A will occur. Event A has P(A) between 0 and 1.0, and it cannot have a negative probability. Therefore, it can be expressed as follows [22]:

$$0 \leq (\mathrm{A}) \leq 1 \tag{1}$$

The complement of P (A) is the probability that $P\left(\widehat{\mathrm{A}}\right)$ that event A does not occur. All possible results are in the "S" sample space. $S \supseteq A =>$ the sum of the probabilities of A and its complement $\widehat{\mathrm{A}}$ must be equal to 1.0:

$$(S) = (A) + P\left(\widehat{\mathrm{A}}\right) = 1 \tag{2}$$

The probability of an expected event is formulated as follows:

$$\text{Probability} = \frac{\text{Expected number of events}}{\text{Number of all possible events}} \tag{3}$$

Bayes' theorem's conditional probability calculations are formulated as follows (Matellini *et al.*, 2013):

$$P(A\,/\,B) = \frac{P(A \cap B)}{P(B)},\ P(B) > 0 \tag{4}$$

$$P(B\,/\,A) = \frac{P(A \cap B)}{P(A)},\ P(A) > 0 \tag{5}$$

Equation (4) in any sample space indicates the probability of the occurrence of event A when event B is known (when event B occurs); Equation (5) shows the probability that event B occurs when event A is known. When Equations (4) and (5) are rearranged, the following equation can be obtained:

$$P(A \cap B) = P(B)P(A\,/\,B) = P(A)P(B\,/\,A) \tag{6}$$

Considering the occurrence of a sample space, the probability of occurrence of any event state A_i is shown as Equation (7).

$$P(A_i\,/\,B) = \frac{P(A_i)P(B/A_i)}{P(B)} \tag{7}$$

3. Methodology

In this study, grounding and collision-contact accidents involving human errors related to the use of electronic navigation devices were investigated with the aim of identifying the errors associated with their use and revealing the effects of these errors on the likelihood of accidents occurring. Accident data was obtained from accident databases, such as the MAIB (Marine Accident Investigation Branch), ATSB (Australian Transport Safety Bureau), EMSA (European Maritime Safety Agency), and NTSB (National Transportation Safety Board), which form the basis of the data set of many accident analysis studies (Table 1) [9, 12,81,92], . The accident reports include accidents occurring on ships over 500 GRT (subject to the SOLAS criteria) and the reasons related to bridge-navigation equipment as the cause of the accident. In accordance with these criteria, 115 grounding and 175 collision-contact accident reports from 2000 to 2017 were examined.

The research consisted of four stages. In the first stage, a Microsoft Excel-based database was created using accident reports. This new database contained several pieces of information, such as ship name, accident date, accident size, type of navigation, and type of ship. The aim of producing this new database was to enable a systematic analysis of accident data. At this stage, the causes of each accident were also determined; the preliminary preparations for the next stage and the HFACS classification were completed. Determination of the causes of each accident and their classification under the HFACS structure was carried out in the presence of a group of 3 domain experts. The expert group in this study has an adequate academic background in marine accident analysis, human factor and HFACS. The experts in the study classified the active failures, latent factors and operational conditions leading to the accidents according to the main structure of HFACS-PV. During the classification, in addition to the definitions in the framework of HFACS-PV, similar studies in the literature were utilized, [77, 78,84,88,92]]. Experts adopted a consensus approach in making final decisions in the classification process. Therefore, results are expected to be obtained with an acceptable consistency. After classification, the causes of accidents associated with the use of electronic navigational devices and their frequencies were placed in a hierarchical structure. In the third stage, a Bayesian network based on the HFACS was established. This network structure made it possible to qualitatively and quantitatively analyse how electronic navigation devices and their improper use

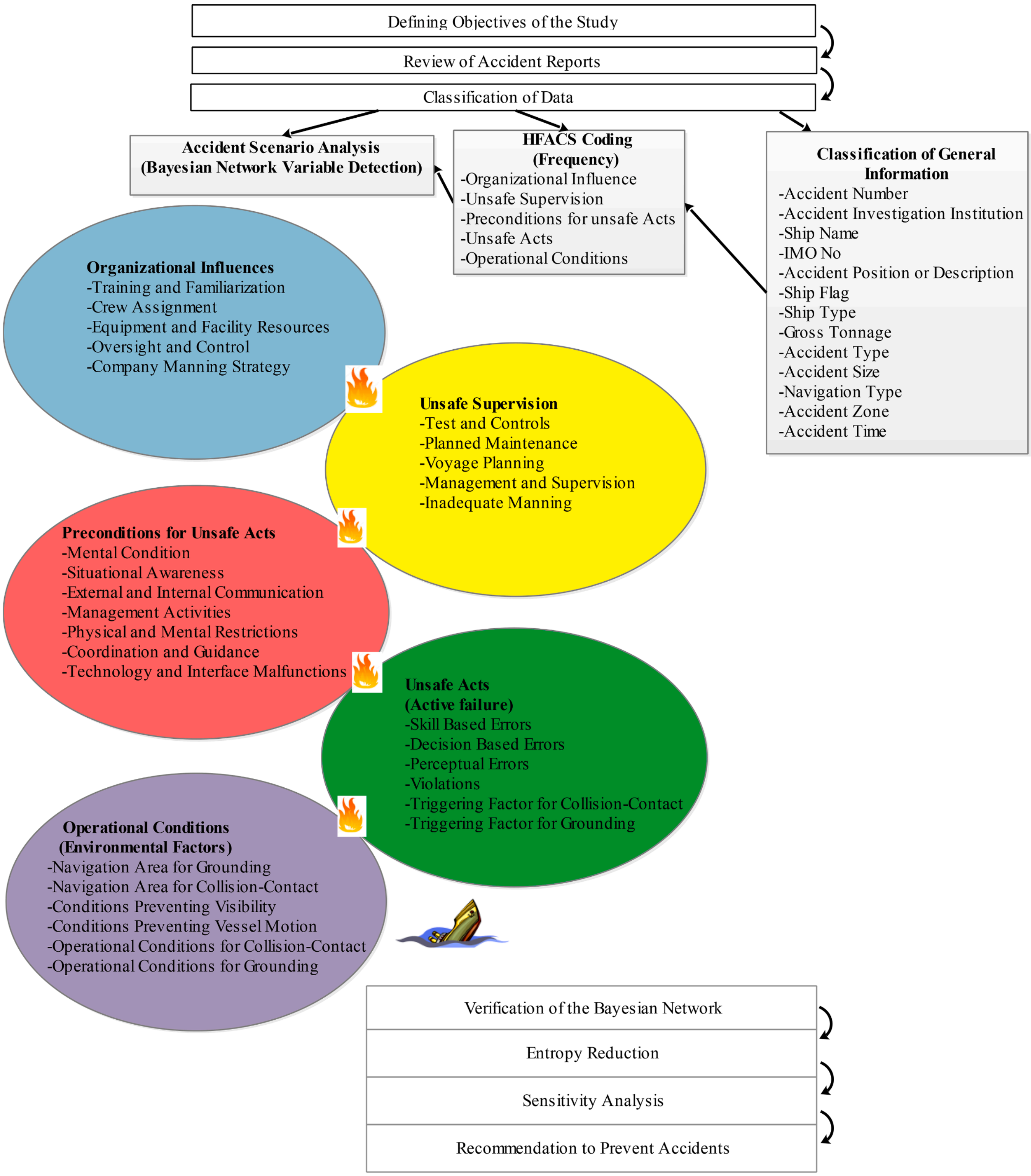


Figure 2. Flow chart of the study

caused accidents. Therefore, the study's Bayesian network structure could be considered an "Accident Network". In previous studies, the conditional probability tables of a Bayesian network were created based on data sets or expert opinions. This is a method that is used when the data set of expert opinions is limited. In this study, conditional probability tables were created based on accident data, as in the studies of Hänninen and Kujala [26]. The details of these tables are presented in Appendix 1. In the accident network, the relationships between the causes of accidents (each node in the Bayesian network) are established by considering the hierarchical structure of the HFACS, accident reports, and the occurrence of accidents. In the study, the steps described above were followed for each accident, and an accident network was created, as given in the "Test Case" section. At the end of the study, all network structures were integrated with each other and the final accident network of the study was constructed. GeNIe software was used to analyse the accident data [4]. Axiom tests were performed to test the

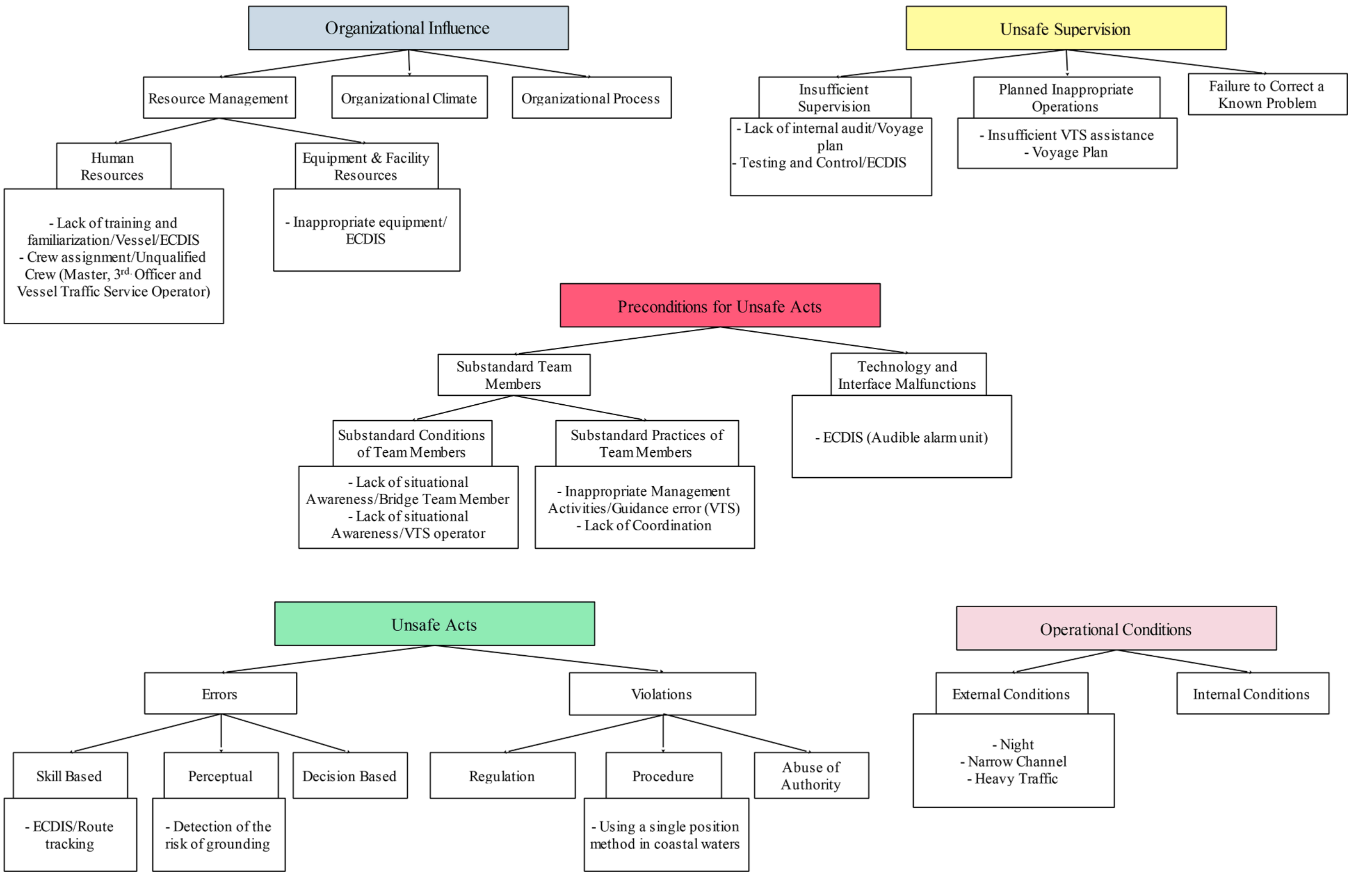


Figure 3. HFACS structure for a test case

accuracy of the Bayesian network. After verifying the accuracy of the network with Axiom tests, entropy reduction and node sensitivity analysis were performed at the last stage. The entropy reduction method was used to determine the nodes to be focused on at each level of the accident network. The effects of these nodes on the accidents were analysed using the sensitivity analysis method. The results demonstrated the effect of the errors made when using bridge-navigation devices on the likelihood of accidents occurring and can be used to determine recommendations to prevent their recurrence. The stages of the study are presented in Figure 2.

4. Test Case

In this step, a sample accident event and the formation of the Bayesian network, sample nodes, and calculations of marginalised and posterior probability values are explained. In this study, test case applications were made in the light of the studies in the previous literature (Matellini *et al.,* 2013, [60]) and they are presented below.

As a test case, M/T Ovit tanker grounding was chosen. The chemical tanker vessel, which departed from the port of Rotterdam in the Netherlands and carried vegetable oil to the Italian Port of Brindisi, was ashore at the exit of the southern band of Dover Strait on the 18^{th} Sept. 2013. The grounding occurred on the night watch. A total of 18 factors played a role in the formation of the grounding. Latent factors, active failures and operational conditions interrelated to lead to the accident are summarized below.

i- Organizational Influence: Unqualified crew assignment (master, 3^{rd} officer and Vessel Traffic Service (VTS) operator), lack of training and familiarization (Electronic Chart Display and Information System (ECDIS)), inappropriate equipment (ECDIS).

ii- Unsafe Supervision: Inappropriate voyage plan, insufficient VTS assistance, insufficient supervision of voyage plan, lack of testing and control (ECDIS).

iii- Pre-condition for Unsafe Act: Lack of situational awareness (bridge team member), lack of situational awareness (VTS operator), malfunctions in the electronic navigations aid/ECDIS (audible alarm unit), guidance error (VTS), lack of coordination, loose team management.

iv- Unsafe Act: Skill-based error/ECDIS (route tracking), perceptual error/failure to detect the presence of the risk of grounding, violations of procedure/using a single position method in coastal waters.

v- Operational Conditions: Night, narrow channel and heavy traffic.

The classification of the accident's causes under the main structure of HFACS for the test case is presented in Figure 3.

In the next step, an accident network was set up based on the HFACS structure. The relationship between the nodes in the Bayesian network relies on the HFACS structure, accident reports and accident occurrences. Therefore, the Bayesian network structure is thought to be reliable and realistic (Figure 4).

4.1. Example of Conditional Probability Calculations

For the sample calculation of conditional probability tables, child node "Oversight and Control" (Adequate/Inadequate) was selected. This node has 3 parent nodes: "Training and Familiarization" (Insufficient/Sufficient), "Legislations and Regulations" (Appropriate/Inappropriate) and "Crew Assignment" (Qualified/Unqualified). The "Oversight and Control" node is dependent on these three nodes (Figure 5).

The "Crew Assignment" and "Legislations and Regulations" nodes are root nodes within these three nodes. The marginalised (unconditional) probability values of these two root nodes based on accident reports are shown below. It was seen that the unqualified crew assignment took place in 63 out of 290 accidents. Therefore, the marginalised probability

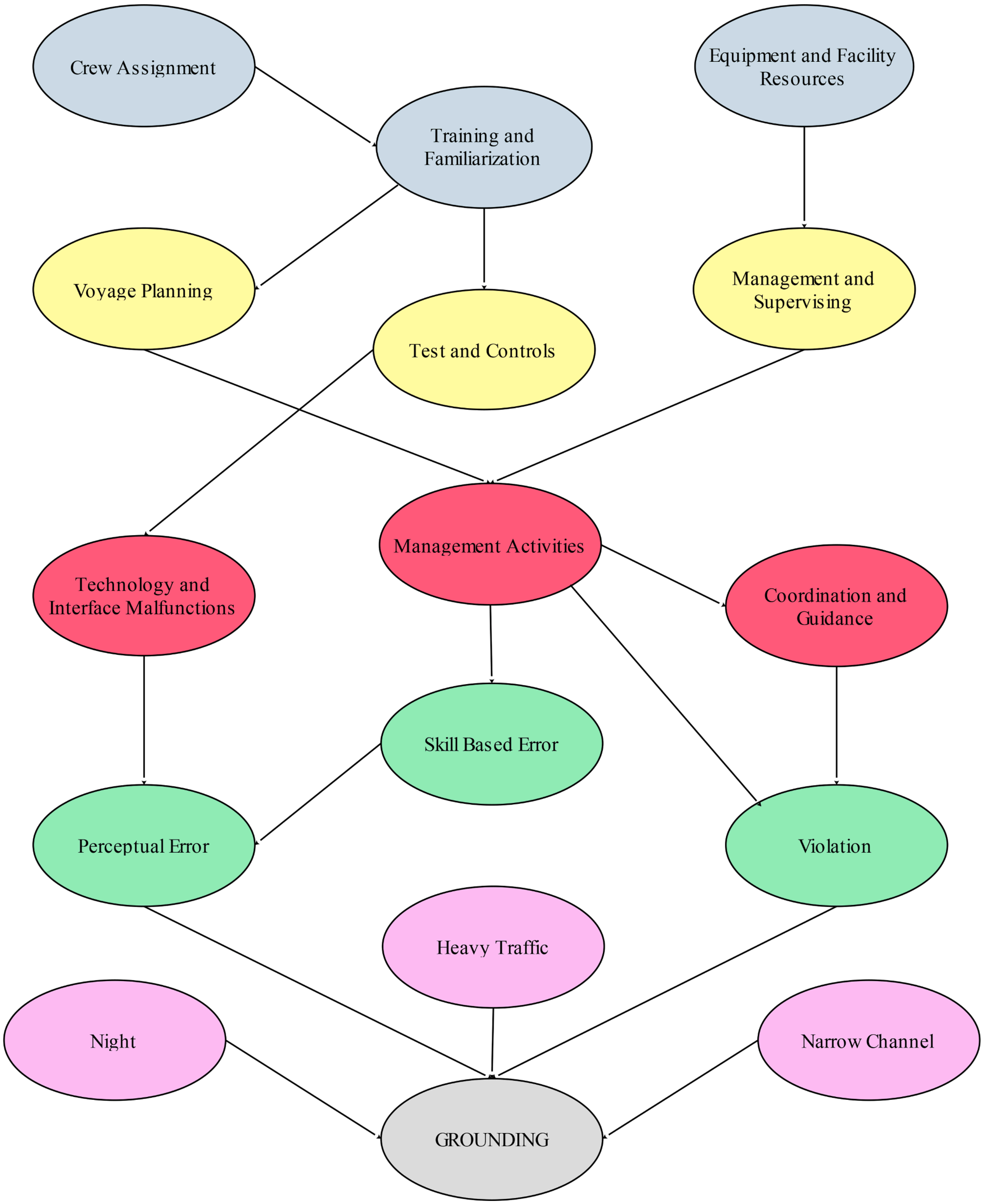


Figure 4. Bayesian Network structure for the test case

value for the "Unqualified" status of the "Crew Assignment" node is calculated as 63/290 = 22% (Equation (3)). The probability value for "Qualified" status is 100% - 22% = 78%. The marginalised probability value of the "Legislations and Regulations" root node for the "Inappropriate" status is 26% (76/290) and 74% (100% - 26%) (Table 2) for the "Appropriate" status.

The "Training and Familiarization" node is chosen for the example of creating conditional probability tables. "Training and Familiarization " node is the child node of the "Crew Assignment" (Figure 5). Depending on the "Crew Assignment" node of the "Training and Familiarization " node, the conditional probability values are calculated as follows (Table 3):

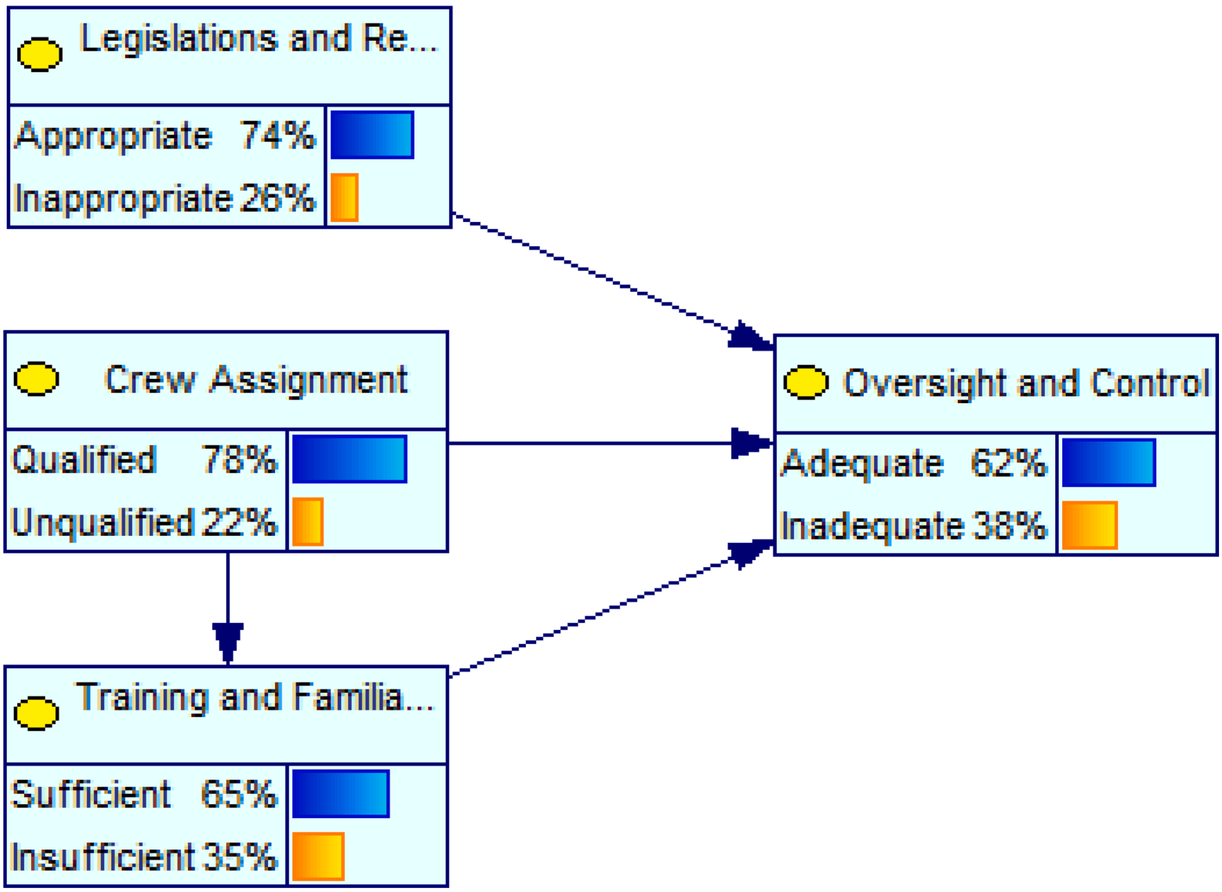


Figure 5. Bayesian network structure for "Oversight and Control" node

Table 2
Table for the marginal probability values of "Crew Assignment" and "Legislations and Regulations" root nodes

Crew Assignment		Legislations and Regulations	
Unqualified (%)	Qualified (%)	Appropriate (%)	Inappropriate (%)
78	22	74	26

Table 3
Calculation of conditional probability values for the Training and Familiarization node

Training and Familiarization		
Sufficient	Insufficient	Crew Assignment
1-(59/227)	59/227	Qualified Crew (observed in 227 accidents)
1-(43/63)	43/63	Unqualified Crew (observed in 63 accidents)

In 63 out of 290 accidents examined, non-conformities due to unqualified crew assignment was observed. Training and familiarization was found to be insufficient in 43 of these 63 accidents. Therefore, the probability of "Training and Familiarization" to be "Insufficient" for the "Unqualified Crew" state of the "Crew Assignment" node is calculated as 43/63 = 0.68. The probability of "Training and Familiarization" to be "Sufficient" for the "Unqualified Crew" status of the "Crew Assignment" node is 1 - 0.68 = 0.32.

Non-conformities related to crew assignment was not found in 227 of the analysed 290 accidents (Table 3). It was observed that in 59 of these 227 accidents, training and familiarization was insufficient. Therefore, for the "Qualified Crew" status of the "Crew Assignment " node, the probability of "Training and Familiarization" to be "Insufficient" is calculated as 59/227 = 0.26. The probability of "Training and Familiarization" to be ''Sufficient" for the ''Qualified Crew'' status of the "Crew Assignment" node is 1 - 0.26 = 0.74. The conditional probability values of the "Training and Familiarization" node based on the "Crew

Table 4
Conditional probability tables for the "Training and Familiarization" node

Training and Familiarization		
Sufficient (%)	Insufficient (%)	Crew Assignment
74	26	Qualified
32	68	Unqualified

Table 5
Conditional probabilities tables for the "Oversight and Control" node

Oversight and Control	Crew Assignment	Legislations and Regulations	Training and Familiarization	
Adequate (%)	Inadequate (%)			
100	0	Qualified	Appropriate	Sufficient
71.5	28.5	Unqualified	Appropriate	Sufficient
64.0	36.0	Qualified	Appropriate	Insufficient
40.4	59.6	Unqualified	Appropriate	Insufficient
10	90	Qualified	Inappropriate	Sufficient
7	93	Unqualified	Inappropriate	Sufficient
5	95	Qualified	Inappropriate	Insufficient
0	100	Unqualified	Inappropriate	Insufficient

Table 6
Nonconformities at the "Organizational Influence" level and their frequencies

		Nonconformities	Collision-contact (*f*)	Grounding (*f*)
Resource Management	Human Resources	**Lack of Training and Familiarization**		
		Vessel		
		Rudder control system	7	7
		Gyro compass	1	5
		AIS (Automatic Identification System)	4	0
		ECDIS (Electronic Chart Display and Information System)	5	10
		Echo sounder	0	5
		Radar	14	2
		BNWAS (Bridge Navigational Watch Alarm System)	0	1
		Vessel's manoeuvring characteristic	13	8
		Navigation Area		
		Pilot unfamiliar with navigational area	4	2
		Bridge team unfamiliar with navigational area	5	5
		Master unfamiliar with navigational area	0	3
		OOW unfamiliar with navigational area	0	1
		Crew Assignment		
		Minimum safe manning	13	10
		Unqualified crew (master, 1st officer, 2nd officer, *etc.*)	42	21
	Equipment & Facility Resources	**Insufficient Equipment and Facilities**		
		Vessel Traffic Services	4	1
		Pilotage service	0	1
		Bridge publications (chart, book, *etc.*)	2	8
		Digital maps - ECDIS	0	1
		ECDIS	0	8
		AIS	5	0
		GNSS (Global Navigation Satellite Systems)	1	0
		BNWAS	0	1
		Inappropriate Equipment and Facilities		
		Fixed or floating navigation aids at port	0	3
		ECDIS - Lack of record mode	1	0
		ECDIS - Unapproved	0	3
		ECDİS - Lack of alarm mode	1	4
		Radar screen	0	1
		Echo sounder	0	1
		Rudder	0	2
		Visual and audio system	1	2
		Ergonomic Design Flaws		
		Bridge ergonomic design (general)	2	10
		Bridge ergonomic design (blind sector)	8	1
		Bridge noise insulation	2	0
		Bridge conning console	1	2
		Bridge engine control panel	2	2
		Bridge navigation equipment location - ECDIS	0	4
		Bridge navigation equipment location - Radar	1	1
		Bridge navigation equipment location - AIS	3	0
		Bridge navigation equipment location - Echo sounder	0	2
Organizational Climate	Organizational Structure	**Communication and Coordination**		
		Chain of Command		
		Distribution of Authority		
	Policies	**Promotion**		
		Drug and Alcohol		
		Inadequate alcohol policy	0	1
	Organizational culture	Irregular watch system	3	5
		Lack of management / Supervision of the ship-owner company	2	1
	Legal Shortcomings			
	Procedure Based			
		Watch system	5	9
		Watch handover	4	4
		Anchorage watch	1	3
		Steering system	0	3
		Navigation safety (restricted water, use cell phone, *etc.*)	8	6
		Bridge familiarization	2	3
		Emergency action plan	3	4
		Bridge team task distribution	2	6
		Command and control of officer	1	0
		Voyage plan	0	2
		Fatigue management	1	5
		Instruction manual - ECDIS	0	2
		Instruction manual - Echo Sounder	0	1
		Instruction manual -VHF radio telephone	1	0
		Legislation Based		
		Certification	2	0
		Standardization	2	1
	Oversight	**Risk Assessment**		

(*continued on next page*)

Table 6 (*continued*)

Nonconformities	Collision-contact (*f*)	Grounding (*f*)
Navigation risk assessment	3	6
Anchorage risk assessment	2	0
Pre-arrival risk assessment	5	0
Pre-departure risk assessment	12	0
Safety Assessment		
Navigation safety bulletin	6	4
Weather forecast	1	1

Assignment" node are presented in Table 4.

The posterior probability value of the "Training and Familiarization" node is 65% for the "Sufficient" status and 35% for the "Insufficient" status (Figure 5).

$$P(a_1) = \sum_{j=1}^{2} P(a_1 b_j)P(b_j) = P(a_1 b_1)P(b_1) + P(a_1 b_2)P(b_2) \tag{8}$$

where a_1=Training and Familiarization (Sufficient), b_1= Crew Assignment (Qualified crew), a_2=Training and Familiarization (Insufficient) and b_2= Crew Assignment (Unqualified crew).

P(TAF= Sufficient) = (0.74 × 0.78) + (0.32 × 0.22 = 0.65 (65%)

The probability of being insufficient of training and familiarization is:

=1-0.65 = 0.35 (35%)

According to the Bayesian network founded in the study, there are 8 conditions in which "Oversight and Control" is adequate or inadequate (Table 5). Considering these conditions, the posterior probability values for the "Oversight and Control" node are 62.25% for the "Adequate" status and 37.75% for the "Inadequate" status (Figure 5).

According to Equations (6) and (7), the probability of the "Oversight and Control" node being "Adequate" is calculated as follows:

$$P(A_i B) = \frac{P(A_i)\ P(B|A_i)}{P(B)},\quad i = 1, 2, 3, 4\ldots,\ k \tag{9}$$

$$P(B) = P(A_1)P(B|A_1) + P(A_2)P(B|A_2) + \ldots + P(A_k)P(B|A_k) = \sum_{j=1}^{k} P(A_j)P(B|A_j) \tag{10}$$

P(OAC=Adequate) = [P(OAC=Adequate|TAF= Sufficient, CA=Qualified Crew, LR= Appropriate)

× P(TAF= Sufficient) × P(CA=Qualified Crew) × (LR=Appropriate)] +

[P(OAC=Adequate|TAF= Sufficient, CA=Unqualified Crew, LR=Appropriate)

× P(TAF= Sufficient) × P(CA=Unqualified Crew) × (LR=Appropriate)] +

[P(OAC=Adequate|TAF=Insufficient, CA=Qualified Crew, LR=Appropriate)

× P(TAF=Insufficient) × P(CA= Qualified Crew) × (LR=Appropriate)] +

[P(OAC=Adequate|TAF=Insufficient, CA=Unqualified Crew, LR=Appropriate)

× P(TAF=Insufficient) × P(CA=Unqualified Crew) × (LR=Appropriate)] +

[P(OAC=Adequate|TAF= Sufficient, CA=Qualified Crew, LR=Inappropriate)

× P(TAF= Sufficient) × P(CA=Qualified Crew) × (LR=Inappropriate)] +

[P(OAC=Adequate|TAF= Sufficient, CA=Unqualified Crew, LR= Inappropriate)

× P(TAF= Sufficient) × P(CA=Unqualified Crew) × (LR=Inappropriate)] +

[P(OAC=Adequate|TAF=Insufficient, CA=Qualified Crew, LR=Inappropriate)

× P(TAF=Insufficient) × P(CA=Qualified Crew) × (LR=Inappropriate)] +

[P(OAC=Adequate|TAF=Insufficient, CA=Unqualified Crew, LR=Appropriate)

× P(TAF=Insufficient) × P(CA=Unqualified Crew) × (LR=Inappropriate)]

P(OAC=Adequate) = [1 × 0.65 × 0.78 × 0.74] + [0.715 × 0.65 × 0.22 × 0.74] + [0.64 × 0.35 × 0.78 × 0.74] +

[0.404 × 0.35 × 0.22 × 0.74] + [0.10 × 0.65 × 0.78 × 0.26] + [0.07 × 0.65 × 0.22 × 0.26] +

[0.05 × 0.35 × 0.78 × 0.26] + [0 × 0.35 × 0.22 × 0.26]

= 0.3752+0.0757+0.1293+0.0230+0.0132+0.0026+0.0035+0

= 0.6225 (62.25%)

The "Oversight and Control" node being "Inadequate" is calculated as follows:

P(OAC=Inadequate) =1-0.6225 = 0.3775 (37.75%) (Figure 5).

5. Classification of Causal Factors in the HFACS Structure

In this study, the coding process was performed regarding the HFACS-PV structure. Coding makes it possible to analyse the causes of accidents systematically. The coding process involved the classification of each cause of the accident according to the HFACS sub-categories. During this process, each cause of accident was assigned a code, or an abbreviation, or explanation in the HFACS structure [8, 43]. During the coding process, the causes and frequencies of accidents were handled independently for each accident category. The operating errors used in the coding and all nonconformities (latent factors, active failures, and operational conditions) leading to their occurrence are detailed in Tables 6-10 for each level of the HFACS. Thus, all nonconformities in the HFACS structure were made comprehensible and clear.

6. Establishment of a Bayesian Network Structure Based on the HFACS Structure

After coding the causes of accidents according to the HFACS main structure, a Bayesian network connected to the main structure was formulated. A Bayesian network is used to demonstrate the relationships between causes in accident analysis studies with the help of nodes. Also, the conditional probability tables in the network mathematically explain how the nodes (causes of accidents) affect each other [27, 62, 90]. The study's expert group has helped establish a Bayesian network for each of 290 accidents by considering HFACS-PV levels, similar studies in the literature, and the occurrence of the accident. Then, by combining the obtained 290 Bayesian networks, the final network of the study was obtained. The expert group has directed an arrow between nodes with a relationship of 5% or more in the 290 Bayesian networks in shaping the final Bayesian network. For example, between the "Training and Familiarization" and "Voyage Planning" nodes, there were relations between 32 of 290 Bayesian networks. Therefore, the arrow was directed between these two nodes in the final Bayesian network. The Bayesian network in this study consists of 32 nodes and 5 levels (Figure 6). Table 11 contains descriptive information about HOFs (Human and Organizational Factors) in the HFACS-PV to which the nodes in the Bayesian network (Figure 6) correspond.

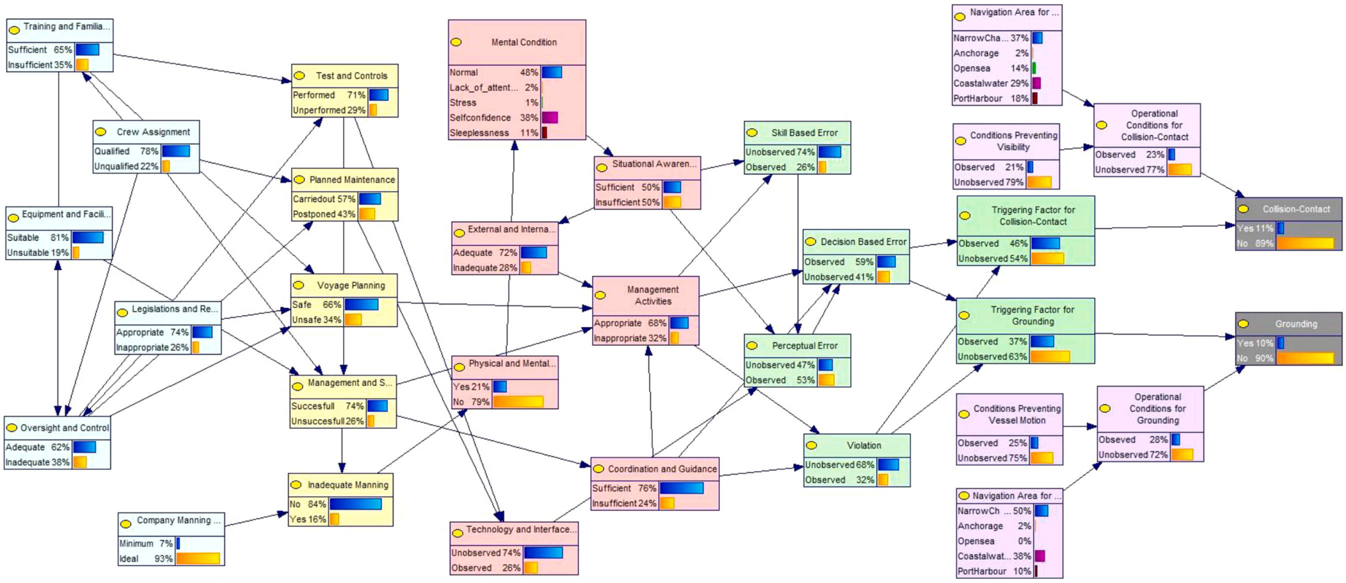


Figure 6. Accident network (Bayesian network) structure for collision-contact and grounding accidents

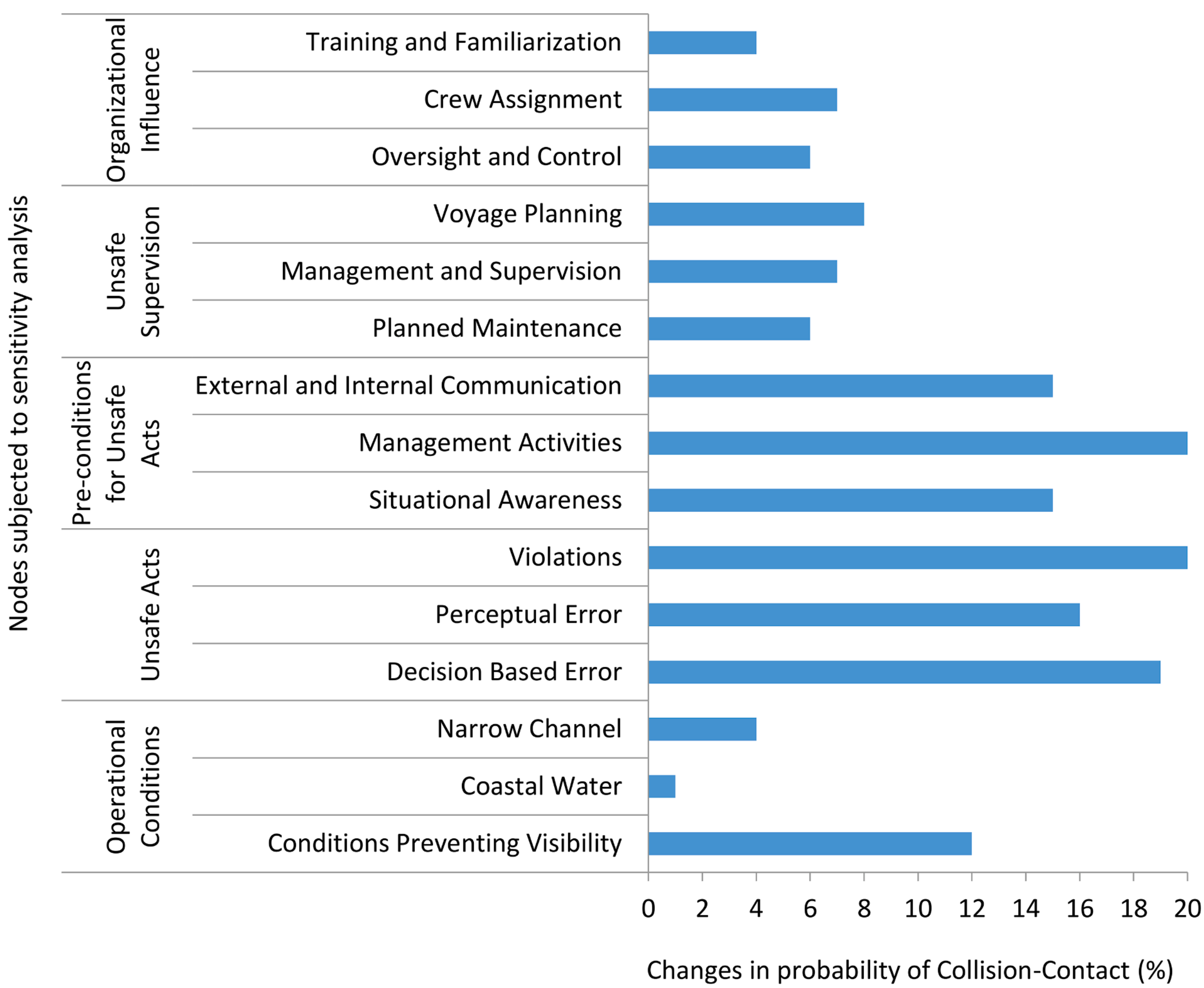


Figure 7. Sensitivity analysis results for Collision-Contact nodes

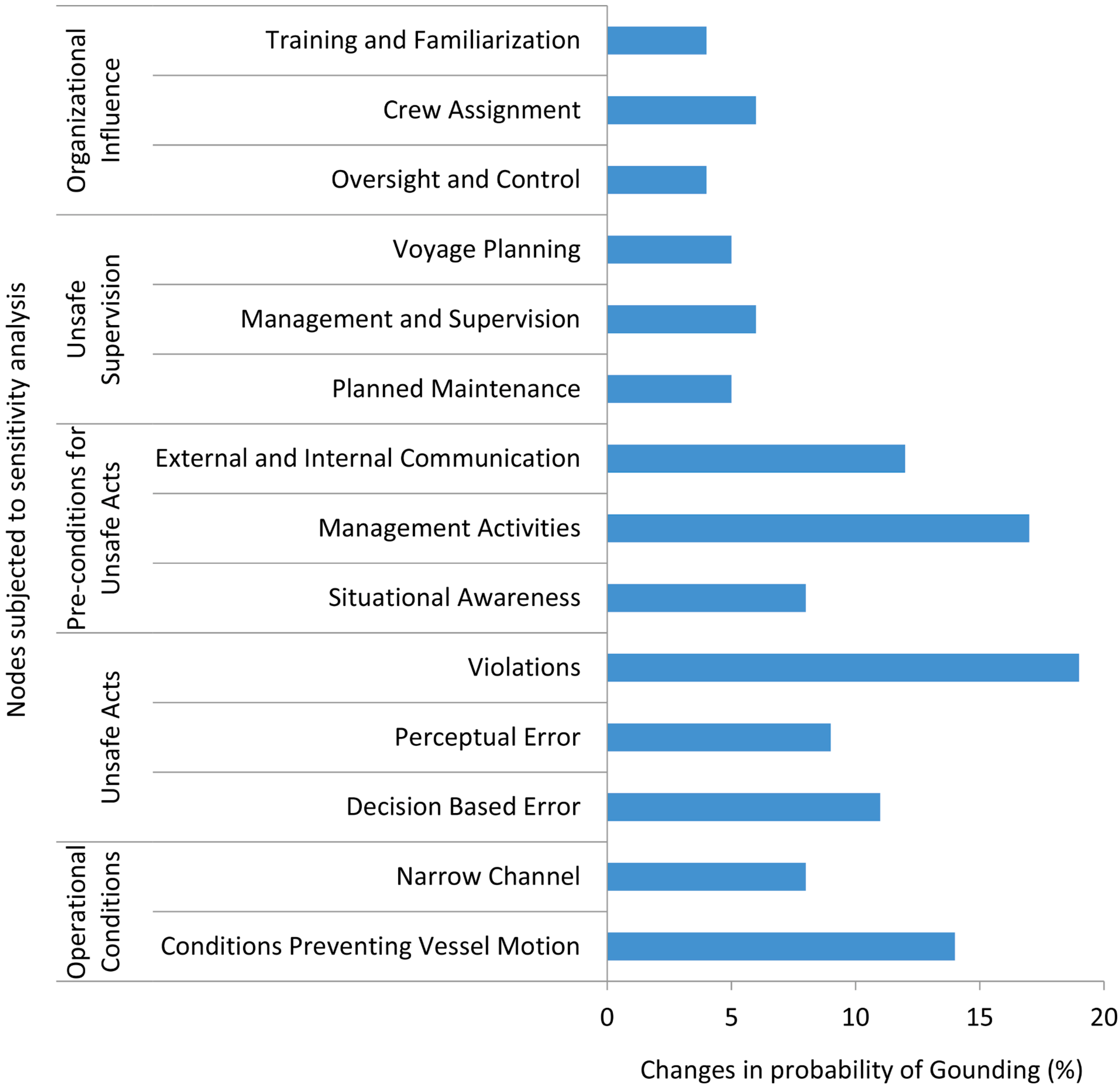


Figure 8. Sensitivity analysis results for Grounding node Abbreviations used in the figure: DBE: Decision Based Error; P: Port-Harbour; CPV: Conditions Preventing Visibility; V: Violation; CW: Coastal Water; OS: Open Sea; A: Anchorage; NC: Narrow Channel

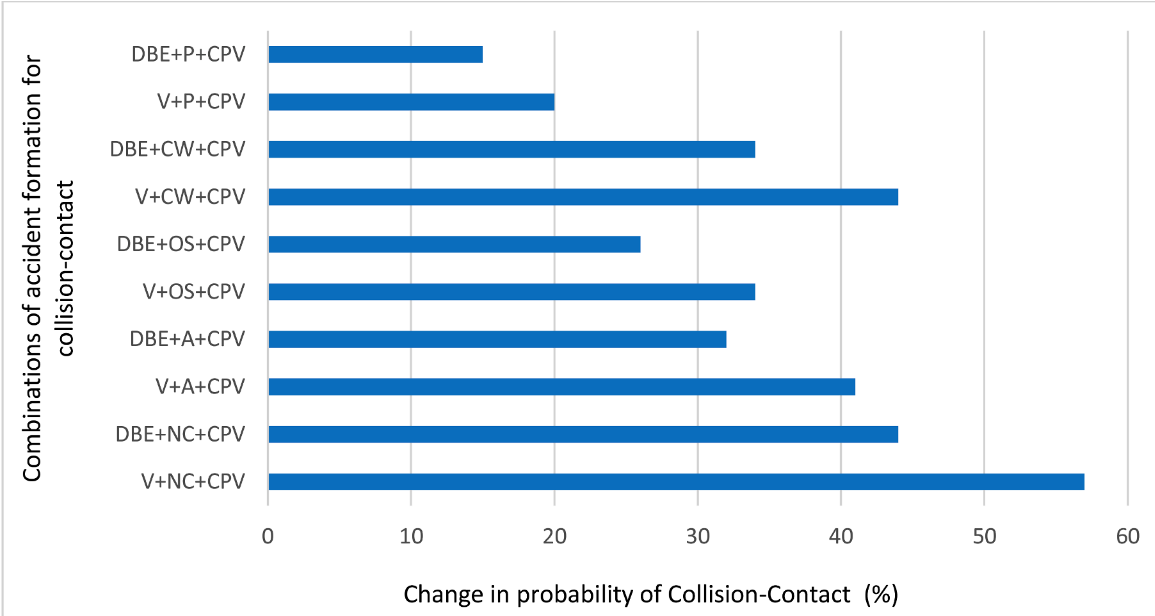
6.1. *Validation of the Bayesian Model*

Axiom tests were performed to prove the accuracy of the Bayesian network established in the study [60]. As a result of the Axiom tests (Axioms 1-3) the validity of the Bayesian network established in the study was proven (Appendix 2).

6.2. *Entropy Reduction and Sensitivity Analysis*

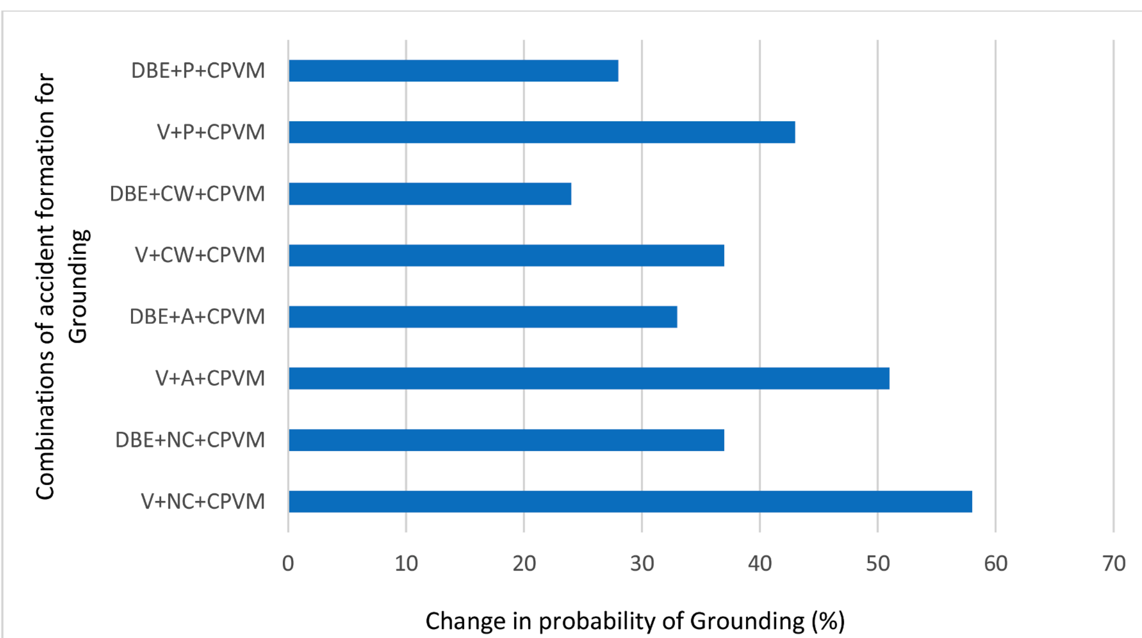
After proving the accuracy of the study with axiom tests, entropy reduction and node sensitivity analysis were performed. Sensitivity analysis helps predict the damage to the system if the adverse event is maximum [78]. In Bayesian network studies, sensitivity analysis reveals the effect of the change in the root nodes, main nodes or sub-nodes of the network on the result nodes. In other words, it allows predicting how changes made in system inputs will affect output [17, 78]. The outputs of this study are collision-contact and grounding, and the inputs are the causes of the accident and operational conditions.

Performing a sensitivity analysis for each node is a time-consuming and challenging task. Instead, it would be more appropriate to identify the nodes that should be focused on at each level. In this study, an entropy reduction method is used to determine the nodes to which sensitivity analysis will be applied. The entropy reduction method in Bayesian network studies is applied to the probability of result nodes, and changes in the respective sub-nodes and main nodes are observed [7, 87]. In this study, entropy reduction is applied for result nodes "Collision-Contact" and "Grounding". In the entropy reduction method, the probability values of the result nodes were made first 0% and then 100%, and the change in other nodes hosted by the network was observed (Table 12). The purpose of entropy reduction in this study is to identify the three most sensitive nodes to be subjected to sensitivity analysis for each HFACS level. The higher the change in probability value of the node due to entropy reduction in a Bayesian network, the more sensitive the node [21]. To explain with an example, when entropy reduction is applied to the "Collision-Contact" node (when the probability value is first 0% then 100%), the most affected nodes by this change is the “Oversight and Control” (12%), “Crew Assignment” (11%) and “Training and Familiarization” (9%) for the first level of HFACS



Abbreviations used in the figure: DBE: Decision Based Error; P: Port-Harbour; CPV: Conditions Preventing Visibility; V: Violation; CW: Coastal Water; OS: Open Sea; A: Anchorage; NC: Narrow Channel

Figure 9. Sensitivity analysis results of accident occurrence combinations for Collision-Contact Abbreviations used in the figure: DBE: Decision Based Error; P: Port-Harbour; CPVM: Conditions Preventing Vessel Motion; V: Violation; CW: Coastal Water; A: Anchorage; NC: Narrow Channel



Abbreviations used in the figure: DBE: Decision Based Error; P: Port-Harbour; CPVM: Conditions Preventing Vessel Motion; V: Violation; CW: Coastal Water; A: Anchorage; NC: Narrow Channel

Figure 10. Sensitivity analysis results of accident occurrence combinations for Grounding

(Organizational Influence) (Table 12). Therefore, the nodes subjected to sensitivity analysis for the first level of HFACS will be these.

In the sensitivity analysis applications, the probability values of the nodes most affected by entropy reduction were first made 0% and then 100%, and the change in the probability of the result nodes was revealed (Figure 7 and Figure 8). The aim of sensitivity analysis applications in accident analysis studies is to quantitatively analyse the impact of accident causes and operational conditions on accident formation. Sensitivity analysis results for the "Collision-Contact" and "Grounding" nodes are presented in Figures 7 and 8.

The final step in the sensitivity analysis is identifying the accident combinations and observing the effect of these combinations on the probability of an accident occurring. The accident network in Figure 6 was created based on the HFACS-PV framework. It would be appropriate to follow Figure 6 to ensure a clear understanding of this section. The network makes it possible to estimate the risk of accident occurrence based on variable conditions. In accordance with the HFACS-PV approach, unsafe acts and operational conditions at the last level of the Bayesian network must coexist for the accident to occur [65,77,78,88]. In other words, marine accidents occur due to unsafe acts and a combination of environmental factors. Each accident contains at least two environmental factors, categorized as positive or negative: 1- Type of navigation and 2- Condition preventing visibility (Observed/Unobserved) or condition preventing vessel motion (Observed/Unobserved). The combinations that caused the accident in this study were created by taking into account the above explanations. Figures 9 and 10 show the sensitivity analysis results of the most possible combinations for each accident category.

7. Results and Discussion

It is inappropriate to connect marine accidents to a single cause or to focus on only a few reasons for their occurrence. To prevent future accidents, their occurrence should be considered holistically. This is possible by fully defining the root causes (unsafe acts), environmental factors and causal factors (latent failures) that are associated with accidents. If the correct relationship can be established between these factors in an accident cycle, it can be understood exactly how the accident occurred. Thus, it becomes possible to offer constructive solutions to prevent accident occurrence. In the Bayesian network based on the HFACS structure, a perfect accident network cycle will emerge if the causes of accidents are correctly linked to each other. In this study, a network structure was created to reveal the effect of nonconformities encountered in the use of new technologies on marine accidents. In this study, it was observed that 1,778 of the factors related to the operating errors that caused the accidents were categorized as collision-contact, and 1,332 were categorized as grounding accidents (Tables 6-10). Accidents are concentrated in coastal waters (grounding: 38%, collision-contact: 29%) and narrow channels (grounding: 50%, collision-contact: 37%) (Table 10). These results are like those of previous studies conducted within the scope of accident analysis ([2, 74],). The prevention of accidents in restricted waterways is possible when training is adequate to ensure the familiarity of the captains with the region and their ships. In this way, captains who pass through restricted waterways can perceive the existing risks before the transition and prevent an accident by making the most appropriate decision for any emergency. 60% of collision-contact accidents and 61% of grounding accidents occurred on the night watch. It was observed that, in 25% of the accidents, there was not a lookout on the bridge. The fact that the accidents studied were concentrated during the night watch and that the absence of a lookout on the bridge was a factor in a quarter of the accidents revealed that there might be a relationship between the likelihood of ship accidents and fatigue. As stated in the studies of Uğurlu [76], Uğurlu *et al.* [79] and [46], working at night negatively affects the energy level of sailors, and fatigue can cause otherwise avoidable errors when there is no lookout on the bridge.

The results of this study related to the accident network are evaluated under the headings below for each level of the HFACS.

7.1. Organizational Influence

According to the Bayesian network sensitivity analysis results, the lack of training and familiarization, and the presence of an unqualified crew were found to be the most critical nonconformities for both accident categories on the organizational influence level (Figures 7 and 8). Lack of training and unfamiliarity with bridges' navigational devices were observed in 61 accidents. A bridge equipped with modern electronic navigation devices can be considered helpful for the officer of the watch (OOW). However, the results of this study and those of Nilsson *et al.* [55], Khan *et al.* [38], and Arif *et al.* [1] showed that officers' lack of education or familiarity with these devices may turn this advantage into a disadvantage. It would be quite risky for OOW/bridge team to use or steer the integrated bridge-navigation devices if they were not familiar with them. In addition, bridge-navigation devices that differ between ships make it difficult to gain familiarity with both a ship and its navigational aids beforehand. Therefore, familiarity must be achieved before boarding the ship so that the issues with a lack of familiarity that may occur during the use of such devices can be eliminated. Bridge-navigation devices, which are continuously becoming more modernized and integrated, require qualified officers and seafarers. According to the BIMCO-ICS [6] human resources report, it is expected that the amount of technologically advanced equipment used on ships will continue to increase until 2025; therefore, new cognitive demands will come to the forefront for future officers. This situation, which will be encountered soon, requires ships to be equipped with qualified

Table 7
Nonconformities at the "Unsafe Supervision" level and their frequencies

	Nonconformities	Collision-contact (*f*)	Grounding (*f*)
Insufficient Supervision	Testing and control - Steering systems	1	4
	Testing and control - Main engine control panel	1	0
	Testing and control - Gyro compass (Error)	1	3
	Testing and control - GPS (Global Positioning System)	0	2
	Testing and control - Echo sounder	0	1
	Testing and control - AIS	12	2
	Testing and control - ECDIS	1	5
	Testing and control - BNWAS	0	18
	Testing and control - Radar	2	0
	Insufficient maintenance - Steering systems	0	6
	Insufficient maintenance - Propeller	1	0
	Insufficient maintenance - Gyro compass	1	0
	Insufficient maintenance - Main engine control panel	1	2
	Lack of internal audit - Voyage plan	0	1
	Lack of internal audit - Officer‘s competency during watch	9	8
	Lack of internal audit - Pilot manoeuvring commands	5	2
	Lack of external audit (Port state control, vetting, flag state control, *etc.*)	3	4
Planned Inappropriate Operations	Voyage plan	15	37
	Lookout - Navigation watch	50	7
	Lookout - Restricted visibility	5	3
	Insufficient pilot, tug, VTS assistance	0	4
	Manoeuvring without tug	0	1
	Assignment of bridge team members according to navigation type	9	5
	Rest and working hours	3	7
Failure to Correct a Known Problem	Uncharted shoal	0	4
	Outdated navigational charts changed buoyage system unapplied on chart	1	3
	Unlit buoy in navigation area	1	1
	Failure to marking of depths in ports	1	2

Table 8
Nonconformities at the "Pre-conditions for Unsafe Acts" level and their frequencies

		Nonconformities	Collision-contact *(f)*	Grounding *(f)*
Substandard Team Members	Substandard Conditions of Team Members	**Adverse Mental Conditions**		
		Lack of situational awareness - Bridge team members	78	35
		Lack of situational awareness - Engine team members	1	1
		Lack of situational awareness - Master	6	3
		Lack of situational awareness - Navigation officer	10	7
		Lack of situational awareness - Helmsman	2	9
		Overconfidence - Bridge team members	7	6
		Overconfidence - Master	18	6
		Overconfidence - Navigation officer	2	0
		Lack of self-confidence - Master	1	5
		Lack of self-confidence - Navigation officer	1	0
		Sleeplessness	3	7
		Stress	1	0
		Lack of attention	23	13
		Overconfidence to electronic navigation equipment-ECDIS	1	6
		Overconfidence to electronic navigation equipment -Radar	16	0
		Overconfidence to electronic navigation equipment - GPS	0	2
		Adverse Physical Conditions		
		Medical illness	3	1
		Physical fatigue of master	1	6
		Physical fatigue of officer	11	19
		Physical fatigue of pilot	19	12
		Physical and Mental Conditions		
		Excessive workload - Officer	2	3
		Master's excessive workload due to pilotage exemption certificate	8	5
		Master's excessive workload due to insufficient number of team members	9	7
		Officer's engagement with cell phone, laptop, *etc.*	14	5
	Substandard Practices of Team Members	**Readiness for Operation**		
		Use of vessel under the influence of drug - Master	1	0
		Use of vessel under the influence of drug - Officer	1	0
		Use of vessel under the influence of alcohol - Master	2	5
		Use of vessel under the influence of alcohol - Officer	0	2
		Inappropriate Management Activities		
		Loose team management	56	55
		Master's lack of authority	7	9
		Failure in management of emergency situations - Blackout	0	2
		Failure in management of emergency situations - Emergency steering gear	9	14
		Guidance error - Vessel traffic service	15	10
		Guidance error - Pilot	7	8
		Lack of Communication		
		Ship to ship (communication problem)	65	3
		Ship to ship (language problem)	7	0
		Ship to VTS	6	3
		Bridge to engine control room	3	0
		Bridge team member	14	17
		Master to officer	0	0
		Officer to lookout	4	2
		Lack of Coordination		
		Pilot to tug	0	0
		Ship to VTS	0	1
Technology and Interface Malfunctions	Malfunctions in the Electronic Navigations Aid	Radar	2	0
		AIS	1	0
		ECDIS	0	2
		GNSS	0	4
		Gyro compass	1	1
		VHF - Radio telephone	1	0
	Interface Malfunctions	Coordinate system - GPS	0	1
		Coordinate system - ECDIS	0	1
		Connection issues related to navigation equipment (Gyro, speed log, *etc.*) - Radar	1	0
		Connection issues related to navigation equipment (Gyro, speed log, *etc.*) - ECDIS	0	1
		Incorrect data - AIS	5	0
		Incorrect data - Portable Pilot Unit (PPU)	0	2
	Other			

seafarers with sufficient training infrastructure. In this study, unqualified crew-related non-compliance was observed as the cause of the accident in 63 incidents (Table 6). As in other studies [29, 36, 44], this study proves that this phenomenon remains a problem for the maritime community. It is impossible to discuss sustainable navigation safety if bridge team members are unqualified. For this reason, shipowners should be more selective than before when appointing crew to their ships. Deficiencies in the oversight and control mechanism can include risk assessment (collision-contact: 29 accidents, grounding: 11 accidents). The nonconformities contained in this node can lead to nonconformities in voyage planning, planned maintenance, and tests and controls (Figure 6).

7.2. Unsafe Supervision

In many previous studies, it was emphasized that the lack of a voyage plan played an important role in collision-contact and grounding accidents [74]. With the developing technology in the maritime industry, voyage plans that used to be complex and time-consuming to prepare can now be prepared in a short period. In addition, thanks to integrated bridge-navigation devices such as the Electronic Chart Display and Information System (ECDIS), Automatic Identification System (AIS), Global Navigation Satellite System (GNSS), and radar, which are hosted by modern bridges, voyage plans are easy to implement and follow. The Bayesian network sensitivity analysis results show the prominence of the voyage plan node for the level of "Unsafe Supervision" (Figures 7 and 8). The study found that there were nonconformities in the voyage plan in 15 collision-contact and 37 grounding accidents (Table 7). The most important reason for this finding is that, when a non-conformity that is overlooked when preparing a voyage plan is combined with other nonconformities, accidents may be unavoidable. The M/T Ovit accident is a good example of this phenomenon [47]. The fact that there was a lack of familiarity with the ECDIS device among officers, the officer in charge of preparing the voyage plan on the M/T Ovit drew the route on the shallows, and the alarm of the ECDIS device did not work were factors that accelerated the occurrence of this accident.

7.3. Pre-Conditions for Unsafe Act

Nodes that stand out at the level of pre-conditions for unsafe acts in the Bayesian network are situational awareness, external and internal communication, and management activities. A lack of situational awareness is encountered when the bridge team's management is unaware of the current situation or conditions. Chauvin *et al.* [8], in their study of a bridge simulator, found that 55% of young officers had a lack of situational awareness. In this study, situational awareness-related deficiencies were observed in 97 of the collision-contact accidents and 55 of the grounding accidents. According to the network created in this study, engagement with other activities during a watch negatively affected situational awareness weakened internal communication and led to inappropriate management activities (Figure 6). The most common types of engagements with other activities during a watch involved mobile phone conversations and laptop use (19 accidents). The most effective way to prevent this situation is to develop an audit-control mechanism and apply corrective sanctions for nonconformities. In this study, as in many previous studies in the literature, it is emphasized that lack of communication is the most significant factor affecting marine accidents [36, 69, 75]. This study's results revealed that a lack of external and internal communication was seen in 99 of the 175 collision-contact accidents and 25 of the 115 grounding accidents. The "Management Activities" node is another important one within this structure. Inappropriate management activities were seen in 72 of the collision-contact accidents and 80 of the grounding accidents (Table 8). Inappropriate management activities included nonconformities such as loose team management, master's lack of authority, and failure in the management of emergency situations (Table 11). As seen in the Bayesian network, the "Management Activities" node is instrumental in the development of nonconformities pertaining to decision-based errors, skill-based errors, and violations (Figure 6).

7.4. Unsafe Act

The focus of this study is the set of inappropriate actions related to bridge-navigation equipment. The first node assessed under this level pertains to skill-based errors. There were 104 nonconformities in collision-contact accidents and 71 nonconformities in grounding accidents. The most common skill-based errors in collision-contact accidents were associated with radar, and for grounding accidents, the most common skill-based errors were associated with the ECDIS and GNSS. The most common skill-based errors regarding radar devices involved the guard zone (24 accidents), the distance and time of the closest point of approach (19 accidents), radar range settings (14 accidents), trial manoeuvres (7 accidents), and parallel index technique (5 accidents) applications. The most common skill-based errors made by OOWs of the ECDIS were cross-tracking errors (6 accidents); regarding the GNSS, cross-tracking (9 accidents) and anchor-watch (13 accidents) errors were the most common ones. One of the most important conclusions drawn from the Bayesian network in this study is that skill-based errors (made during device use) caused perceptual errors. Skill-based errors made during the use of bridge navigation devices could result in the development of perceived nonconformities, such as an inability to detect the presence of the target ship, detect the behaviour of the target ship, solve the problem in the system (Table 6). Unless devices are carefully and correctly managed, the workload of the officer doing the watchkeeping will increase under these circumstances, and it will become difficult to detect potential hazards. In this case, it is inevitable that ships' officers will make misguided decisions under the appropriate operational conditions, decisions will be delayed, or no action will be taken against dangerous situations, and accidents will become inevitable. The only way to avoid such accidents is to design hardware, software, and warning systems that prevent skill-based errors that occur through human-device interaction and make them available to ships' officers.

Another node at this level is the perceptual error. There were 159 perception-based nonconformities in collision-contact accidents and 107 in grounding accidents. The studies in the literature emphasize that situational awareness and a crew's unsafe acts (skill-based errors) have an indirect effect on subjective risk assessments (perceptual errors) [13, 20,64]. This study reveals that technology and interface failures may affect perceptual- and indirect decision-based errors in addition to these two elements.

Decision-based errors include late, faulty, and unstable manoeuvring by navigation officers. This type of error involves adopting the incorrect course of action in the face of a negative situation or failing to adopt the correct course of action in time. Nonconformities related to this node were identified 141 times in collision-contact accidents and 105 times in grounding accidents. Today's electronic navigation aids and their associated systems are based on advanced monitoring and control systems that ensure the safe navigation of ships. However, the fact that the existing systems are incapable of being completely independent (autonomous) decision-makers or implementers requires a human watch officer to be included in the decision mechanism. Decision-based errors are much more complex than perceptual and skill-based ones. As can be seen from the Bayesian network, there are many components that can cause issues to emerge. Currently, the lack of fully autonomous ships results from the failure to understand exactly how to solve decision-based errors.

Violations are divided into three sub-categories: regulations, procedures, and abuse of authority. Nonconformities related to this node were identified 246 times in collision-contact accidents and 159 times in grounding accidents. This node is the most instrumental one in the formation of collision-contact and grounding accidents. Violations arose

Table 9
Nonconformities at the "Unsafe Acts" level and their frequencies

	Nonconformities	Collision-contact *(f)*	Grounding *(f)*	
Errors	Skill Based	Radar - Guard zone	24	0
		Radar - CPA (Closest Point of Approach) and TCPA (Time of Closest Point of Approach)	19	0
		Radar - Gain / Tune setting	4	0
		Radar - Range setting	14	0
		Radar - Display mode (north up-course up-head up)	2	0
		Radar - Motion mode (true-relative)	4	0
		Radar - Parallel index	0	5
		Radar - Visual target detection	1	0
		Radar - Clutter setting (rain and sea)	4	0
		Radar - Trial manoeuvre	7	0
		GNSS - Voice alarm setting	0	2
		GNSS - Display and dimmer setting	0	1
		GNSS - Datum selection	0	2
		GNSS - Anchor watch	4	9
		GNSS - Cross tracking error	0	6
		Echo sounder - Depth alarm	0	5
		Echo sounder - Range scale and setting	0	1
		Rudder - Steering control system	4	7
		Navigational Telex (NAVTEX) - Station selection	2	1
		ECDIS - Cross tracking error	0	12
		ECDIS - Check route setting	0	1
		ECDIS - Look ahead setting	0	2
		ECDIS - Chart alarm setting	0	1
		ECDIS - Visual target detection	3	8
		Steering control panel	2	6
		Auto pilot - Steering control system	2	1
		Engine control system - Control panel	5	1
		AIS-Visual target detection device	3	0
	Decision Based	Faulty manoeuvring - Master	26	24
		Faulty manoeuvring - Officer	24	12
		Faulty manoeuvring - Pilot	5	6
		Late in manoeuvring - Master	17	3
		Late in manoeuvring - Pilot	11	14
		Late in manoeuvring - Officer	20	15
		Insufficient manoeuvre command (rudder angle, reduce speed, *etc.*)	18	5
		Inappropriate route selection	1	14
		Deviation from the planned route	2	9
		Incorrect decision to reduce the speed	14	0
		Improper anchorage manoeuvring (drop, adrift)	1	2
		Anchorage area selection	2	1
	Perceptual	Failure to detect the presence of the risk of collision	19	0
		Failure to detect the presence of the risk of grounding	0	32
		Failure to detect the target (vessel, buoy, *etc.*)	60	3
		Failure to understand the target vessel's intention	3	1
		Failure to understand the effects of wind and current	4	10
		Incorrect interpretation of navigation data - ECDIS	1	1
		Position - ECDIS	0	23
		Incorrect interpretation of navigation data - GNSS	0	1
		Failure to detect systemic problem - GNSS	1	3
		Position - GNSS	0	10
		Failure to detect systemic problem - Gyro	1	0
		Failure to detect systemic problem - Steering control system	2	7
		Incorrect interpretation of navigation data - Radar	2	0
		Closest passing time and distance - Radar	6	0
		Target vessel's movement - Radar	8	0
		Presence of target vessel - Radar	42	0
		Distance measurement - Radar	1	0
		Presence of target vessel - AIS	5	0
		Course and rudder angle - Steering control system	2	7
		Depth and under keel clearance - Echo sounder	0	6
		Auditory lookout - VHF	2	0
		Navigational warnings - NAVTEX	0	3
Violations	Regulation	COLREG Rule 2 (responsibility in the risk of collision situation)	19	0
		COLREG Rule 5 (lookout)	62	13
		COLREG Rule 6 (safe speed)	24	7
		COLREG Rule10 (traffic separation scheme)	6	0
		COLREG Rule 13 (overtaking)	8	0
		COLREG Rule 14 (head-on situation)	4	0
		COLREG Rule 15 (crossing situation)	12	0
		COLREG Rule 19 (conduct of vessels in restricted visibility)	6	0
		COLREG Rule 22 (visibility of lights)	4	0
		COLREG Rule 34 (manoeuvring and warning signals)	31	0
		COLREG Rule 35 (sound signals in restricted visibility)	7	1
		Watch handover (STCW)	6	0
		Unmanned bridge (STCW)	0	1
		Working and resting hours (ILO)	3	7
	Procedure	Company procedures - Routine checks of ship's position	0	52
			1	4

(*continued on next page*)

Table 9 (*continued*)

Nonconformities		Collision-contact (*f*)	Grounding (*f*)
	Company procedures -Way point not entered in GNSS / ECDIS		
	Company procedures - Alcohol	2	4
	Company procedures - Heave up anchor during heavy sea condition	0	1
	Company procedures - Unsafe passage	5	0
	Master's standing orders	16	6
	Device updates - ECDIS	0	5
	Device updates - AIS	4	0
	Rudder control system - Use of emergency rudder	2	9
	Rudder control system - Use of steering engine	3	1
	Unused device - Radar	1	0
	Unused device - ECDIS	0	4
	Unused device - BNWAS	3	19
	Unused device - Echo sounder	0	11
Abuse of Authority	Ignored the warning of VTS	2	3
	Misinformation - Pilot	3	4
	Turn off the alarms - Radar	6	0
	Turn off the alarms - ECDIS	3	4
	Turn off the alarms - Steering control system	1	1
	Turn off the alarms - Echo sounder	0	2
	Turn down the volume - VHF radio telephone	2	0

because of inappropriate management activities and the inability to provide management and guidance, and are the final conditions necessary for an accident to occur (Figure 6). COLREG (Convention on the International Regulations for Preventing Collisions at Sea) violations were the most instrumental ones in collision-contact accidents (Table 9). COLREG Rule 5 (improper lookout), COLREG Rule 6 (unsafe speed), COLREG Rule 2 (responsibility in case of risk of collision), and COLREG Rule 34 (failure to provide sound and light warnings in case of risk of collision), are the most violated COLREG rules concerning collision-contact accidents. The findings are consistent with the COLREG violations reported in previous studies [49,74]. For grounding accidents, procedural violations, rather than regulatory ones, play a large role in accident occurrence (Table 9). 49 of these violations were related to the use of electronic navigation aids. It has been observed that, in grounding accidents, especially those associated with the use of the Bridge Navigational Watch Alarm System (BNWAS), rudder control systems and echo sounder devices caused them. The most common procedural violations involved the closure of these devices in coastal areas, especially in ports, narrow channels, and anchorage areas. It is unacceptable to leave these devices disabled during navigation, especially during the night watch.

7.5. *Operational Conditions*

Another category that is instrumental in the occurrence of accidents consists of operational conditions. There is an interaction between operational conditions (fog, currents, wind, tides, *etc.*) and unsafe actions rather than a cause-and-effect (Ugurlu *et al.,* 2018). As a result of this interaction, ship accidents occur. Spatial constraints (narrow channels, coastal waters) and visibility restrictions (fog, environmental lights) were found to be complementary factors in the occurrence of accidents (Figure 6). The Bayesian network's sensitivity analysis results show that narrow channels were a factor in collision-contact accidents, and rain and fog were included in the conditions affecting visibility. In this study, although the night was not considered a visibility restriction, it was involved in 104 collision accidents and 70 grounding accidents. This reveals the effect of the night on the likelihood of accidents occurring. The operational conditions that stand out in grounding accidents are narrow channels and conditions that prevent a ship's movement. The results obtained during this study are like those shown in other studies [11, 85, 92]. However, the existing risks can be eliminated by choosing personnel who are familiar with the region and ship.

7.6. *General Considerations*

According to the Bayesian network's sensitivity analysis results, for collision-contact accidents (Figure 7), the most likely accident scenario occurred when a violation (COLREG, STCW, *etc.*) was made in combination with restricted visibility in a narrow channel. It was shown that, in such a situation, the probability of a collision increased by 57%. When

Table 10
Nonconformities at the "Operational Conditions" level and their frequencies

		Nonconformities	Collision-contact (*f*)	Grounding (*f*)
External Conditions	Weather Conditions	**Conditions Preventing Visibility**		
		Fog	34	6
		Rain	5	0
		Night	104	70
		Environmental lights	3	1
		Sun reflection	2	0
		Conditions Preventing Vessel Motion		
		Ice	1	5
		Current	2	13
		Heavy sea conditions	5	16
		Tide	1	2
		Squat	0	2
	Locational Restrictions	Port/Harbour	32	11
		Coastal waters	50	44
		Anchorage area	4	2
		Open Sea	24	0
		Narrow channels / Strait	65	58
		Dense traffic	15	8
Internal Conditions	Non- conformities and Failures	Engine malfunction	3	1
		Controllable Pitch Propeller (CPP) malfunction	2	0
		Bow thruster malfunction	0	1
		Rudder failure	0	11
		Loss of power	0	1
	Vessel Structural Defects			

Table 11
Nodes in the Bayesian network and their nonconformities

HFACS Level	Node	Abbreviation	Nonconformities on the Node	Negative Expression	Probability (%)	Parent Nodes
Organizational Influence	Training and Familiarization	TAF	- Lack of training and familiarization-Vessel - Lack of training and familiarization-Navigation area	Insufficient	35	CA
	Crew Assignment	CA	- Unqualified crew (master, 1^{st} officer, 2^{nd} officer, *etc.*)	Unqualified	22	Root node
	Equipment and Facility Resources	EFR	- Insufficient equipment and facilities - Inappropriate equipment and facilities - Ergonomic design flaws	Unsuitable	19	OC
	Legislations and Regulations	LR	- Legal shortcomings / Procedure based - Drug and alcohol policy - Operation management - Legal shortcomings / Legislation based	Inappropriate	26	Root node
	Oversight and Control	OAC	- Risk assessment - Safety assessment	Inadequate	38	TAF, CA, LR
	Company Manning Strategy	CMS	- Minimum safe manning	Minimum safe manning	7	Root node
Unsafe Supervision	Test and Controls	TC	- Testing and control - Bridge navigation equipment (ECDIS, AIS, Radar, steering systems, *etc.*)	Unperformed	29	TAF, OC
	Planned Maintenance	PM	- Insufficient maintenance	Postponed	43	OC, CA
	Voyage Planning	VP	- Voyage plan	Unsafe	34	TAF, OC, LR
	Management and Supervision	MS	- Lack of internal audit - Lack of external audit - Rest and working hours - Manoeuvring without tug - Insufficient pilot, tug and VTS assistance - Failure to correct a known problem	Unsuccessful	26	EFR, CA, TC
	Inadequate Manning	IM	- Lookout - Navigation watch - Lookout - Restricted visibility - Assignment of bridge team members according to navigation type	Yes	16	CMS, MS
Pre-conditions for Unsafe Acts Normal: 48	Mental Condition	MC	- Overconfidence - Self-confidence - Sleeplessness - Stress - Lack of attention	Lack of Attention:2 Stresful:1 Overconfidence:38 Sleeplessness:11	PMR	
	Situational Awareness	SA	- Lack of situational awareness	Insufficient	50	MC
	External and Internal Communication	EIC	- Lack of communication	Inadequate	28	SA
	Management Activities	MA	- Loose team management - Master's lack of authority - Failure in management of emergency situations - Blackout - Failure in management of emergency situations - Emergency steering gear	Inappropriate	32	EIC, MS, VP, CG
	Physical and Mental Restrictions	PMR	- Adverse physical conditions - Physical and mental conditions - Readiness for operation	Yes	21	IM
	Coordination and Guidance	CG	- Guidance error - Lack of coordination	Insufficient	24	MA
	Technology and Interface Malfunctions	TIM	- Malfunctions in the electronic navigations aid - Interface malfunctions - Others	Observed	26	PM, TC
Unsafe Acts	Skill Based Error	SBE	Errors / Skill based	Observed	26	SA, MA
	Decision Based Error	DBE	- Errors / Decision based	Observed	59	MA, CG, PBE
	Perceptual Error	PBE	- Errors / Perceptual	Observed	53	SA, SBE, TIM
	Violations	V	- Regulation - Procedure	Observed	32	MA, CG
	Triggering Factor for Collision-Contact	TFC	- Abuse of authority	Observed	46	DBE, V

(*continued on next page*)

Table C1 (*continued*)

HFACS Level	Node	Abbreviation	Nonconformities on the Node	Negative Expression	Probability (%)	Parent Nodes
	Triggering Factor for Grounding	TFG		Observed	37	DBE, V
Operational Conditions	Navigation Area for Grounding	NAG	- Narrow channel (NC) - Port-Harbour (P) - Anchorage (A) - Coastal water (CW)	Narrow channel: 50 Port: 10 Anchorage: 2 Coastal water: 38	Root node	
	Navigation Area for Collision-Contact	NAC	- Narrow channel - Port-Harbour - Anchorage - Coastal water - Open sea (OS)	Narrow channel: 37 Port: 18 Anchorage: 2 Coastal water: 29 Open Sea: 14	Root node	
	Conditions Preventing Visibility	CPV	- Fog - Rain - Environmental lights - Sun reflection - Night	Observed	21	Root node
	Conditions Preventing Vessel Motion	CPVM	- Non- conformities and failures preventing ship's motion - Ice, current, heavy sea conditions, tide, squat - Dense traffic	Observed	25	Root node
	Operational Conditions for Collision-Contact	OPCC		Observed	23	CPV
	Operational Conditions for Grounding	OPCG		Observed	28	CPVM
Consequence Node	Collision-Contact	-		Yes	11	OPCC, TFC
	Grounding	-		Yes	10	OPCG, TFG

the same situation occurred in coastal waters instead of narrow channels, the probability of collision increased by 44%. In addition, it was seen that decision-based errors affected collision-contact accidents. It was observed that the probability of an accident increased by 44% when decision-based errors were made in a narrow channel with restricted visibility (Figure 9).

Grounding accidents were most likely when there was a combination of a violation in a narrow channel (58%) and conditions that could prevent vessel motion. When the same situation occurred in an anchorage, the probability of an accident increased by 51% (Figure 10). Navigation type is significant in accident occurrences, and narrow channels are the marine area where both types of accidents are most likely to occur, which is consistent with the studies in the existing literature. Similar results were obtained in the studies in which Uğurlu *et al.,* [74] dealt with ship accidents occurring involving oil tankers. The possibility of both grounding and collision-contact accidents being concentrated in narrow channels reveals the need to focus on preventive measures in this area.

8. Conclusion

With the presence of much more modern and integrated navigation systems in bridges than ever before, shipping and the handling of ships has become much easier. It is possible to use the new applications of such technology in the most effective way by familiarising officers with them. However, incompatibilities encountered in the operation of technological devices can cause accidents. This study was conducted to reveal the place and importance of technology in ship accidents. In the study, a network structure that summarises the occurrence of ship accidents based on the HFACS framework is presented. The critical results and recommendations found in the study are explained below:

- The network structure presented in this study allows analysing the impact of nonconformities encountered in the operation of technological devices on accident occurrence. With the help of conditional probability tables, it has become possible to analyse the root causes, causal factors, and operational conditions that cause accidents, and observe how these factors affect accidents. Marine accident investigators can understand the occurrence of the accident, which they will examine, by considering each node in the accident network presented in this study and the relationship between the nodes.
- Unqualified crew assignment and lack of training and familiarization were found to be the most critical factors at the organizational influence level. The most common nonconformities under the title of training and familiarization are the lack of familiarity with ship equipment or the voyage area. It is impossible to maintain sustainable navigation safety with its unqualified bridge crew unfamiliar with these devices. Adoption of training programs that will ensure seafarers' familiarity with the bridge and the navigational aids before embarking on the ship can be effective in preventing accidents.
- The results of this study revealed that accidents occurred due to the inactivation of the BNWAS device, especially during night watches. Therefore, it is necessary to prevent the BNWAS device from being deactivated by the ship's personnel during navigation. For example, the automatic activation of the device by the operation of the main engine and not being taken into a passive position as long as the main machine is running can be considered a solution. Also, adding software to the BNWAS device to show working hours and controlling the device's working hours records during port or flag state control inspections may effectively prevent accidents caused by fatigue and lack of situational awareness.
- The accident network has shown that skill-based errors made in bridge-navigation devices did not cause the accident directly. All

Table 12
Applications of entropy reduction for the collision-contact and grounding nodes

HFACS Level	Node		Entropy Reduction for Collision-Contact (%)	Entropy Reduction for Grounding (%)	Collision-contact		Grounding	
					100 (%)	0 (%)	100 (%)	0 (%)
Organizational Influence	Training and Familiarization		9	9	43	34	43	34
	Crew Assignment		11	10	32	21	31	21
	Equipment and Facility Resources		6	6	24	18	24	18
	Legislations and Regulations		6	7	31	25	32	25
	Oversight and Control		12	12	48	36	48	36
	Company Manning Strategy		1	1	8	7	8	7
Unsafe Supervision	Test and Controls		10	10	38	28	38	28
	Planned Maintenance		13	13	54	41	54	41
	Voyage Planning		13	14	45	32	46	32
	Management and Supervision		13	12	37	24	36	24
	Inadequate Manning		11	8	25	15	23	15
Pre-conditions for Unsafe Acts	Mental conditions	Normal	-24	-16	26	50	33	49
		Lack of Attention	2	2	4	2	4	2
		Stressful	0	0	1	1	1	1
		Overconfidence	15	9	51	36	46	37
		Sleeplessness	9	6	19	10	17	11
	Situational Awareness		43	21	80	47	69	48
	External and Internal Communication		26	26	51	25	51	25
	Management Activities		37	40	65	28	68	28
	Physical and Mental Restrictions		14	10	33	19	30	20
	Coordination and Guidance		12	13	35	23	36	23
	Technology and Interface Malfunctions		10	10	35	25	35	25
Unsafe Acts	Skill Based Error		21	33	54	23	56	23
	Decision Based Error		41	29	96	45	85	56
	Perceptual Error		35	23	84	49	74	51
	Violations		40	44	68	28	72	28
Operational Conditions	Conditions Preventing Visibility		21	-	40	19	-	-
	Conditions Preventing Vessel Motion		-	29	-	-	51	22
	Local Restrictions for Collision-Contact	Narrow Channel	16	-	51	35	-	-
		Anchorage	-1	-	1	2	-	-
		Open Sea	-4	-	10	14	-	-
		Coastal Water	4	-	33	29	-	-
		Port	-15	-	5	20	-	-
	Local Restrictions for Grounding	Narrow Channel	-	8	-	-	57	49
		Anchorage	-	0	-	-	2	2
		Coastal Water	-	-7	-	-	32	39
		Port	-	-1	-	-	9	10

nonconformities under skill-based errors affect perception negatively (Table 9). Also, perceptual errors were found to be one of the important factors that caused decision-based errors. Decision-based errors, combined with appropriate environmental conditions, directly cause an accident. It does not cause the formation of any other non-conformities such as skill-based errors or perceptual errors. Therefore, the consequences are severe, and it is essential to identify the underlying non-conformities in order not to make these errors again in the future.

- Violations of regulations are the most frequently observed unsafe acts, especially in collision-contact and have the most significant impact on accidents. The most common violation under this framework is the COLREG violation. It would be helpful to define the COLREG rules to the devices through the interface software to be added to the bridge electronic navigation devices and to provide the OOW with recommendations to prevent the occurrence of accidents by these devices. Thus, the officer will be able to make the safest manoeuvre by considering the offers of the device in case of accident risk. The allocation of intelligent systems to detect danger in the bridge may be considered an accident prevention solution. The automatic adjustment of the user settings in the appropriate devices (RADAR, ECDIS, echo sounders, *etc.*) by considering the risk factors such as traffic density, visibility and regional restriction by the intelligent systems may be effective in preventing OOW-induced errors (skill-based errors). In such an environment, OOWs' role in the bridge will be the decision-making mechanism. The officer is obliged to perform safe action taking into account all processed data associated with the technology. Thus, it would be ensured that the OOW reacts quickly and on time to events.
- It was found that both grounding and collision-contact accidents were concentrated in narrow channels. The prevention of accidents in these restricted waters can be achieved by ensuring that the masters are familiar with the operational area. In this context, creating new training modules at the IMO and conducting these training in the presence of local marine pilots can be considered as a measure to prevent accidents in restricted waters. Thus, masters passing through these restricted waters will perceive the existing risks before the passage, avoid possible accidents by making the most appropriate manoeuvre in an emergency that may occur, or minimize the consequences that may arise if the accident occurs.

In this study, the most common user mistakes made by officers in bridge-navigation devices were determined. In future studies, researchers' work on decision support systems and software that will minimize these errors may help prevent skill-based error. It has been observed that the insufficiency of the existing fault warning systems on the bridge-navigation devices may also cause accidents. Therefore, it will be useful to develop integrated software that will detect interface malfunctions. If incorrect information given by one device is detected by another with warnings given to the OOW, it will increase the officer's situational awareness on the bridge.

Credit Author Statement

Mehmet KAPTAN: Conceptualization, Investigation, Writing - Original Draft, Software, Formal analysis, Validation, **Özkan UĞURLU:** Original Draft, Software, Formal analysis, Validation, Supervision, Writing - Review & Editing, **and Jin WANG:** Supervision, Writing - Review & Editing.

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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Supplementary materials

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