Analysing of Collision, Grounding and Sinking Accident Occurring in the Black Sea Utilizing HFACS and Bayesian Networks

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ABSTRACT

This study examines and analyses marine accidents that have occurred over the past 20 years in the Black Sea. Geographic Information System (GIS), Human Factor Analysis and Classification System (HFACS) and Bayesian Network (BN) models are used to analyse the marine accidents. The most important feature that distinguishes this study from other studies is that this is the first one to analyse accidents that have occurred across the whole Black Sea. Another important feature is the application of a new HFACS structure to reveal accident formation patterns. The results of this study indicate that accidents occurred in high concentrations in coastal regions of the Black Sea, especially in the Kerch Strait, Novorossiysk, Kilyos, Constanta, Riva and Batumi regions. The formation of grounding and sinking accidents has been found to be similar in nature, with the use of inland and old vessels being highlighted as important factors regarding sinking and grounding incidents. However, the sequence of events that lead to collision-contact accidents differs from those events which form grounding and sinking accidents. This study aims to provide information to the maritime industry regarding the occurrence of maritime incidents in the Black Sea, in order to assist with accident reduction and prevention.

KEY WORDS: GIS, HFACS, Bayesian network, accident analysis, marine accident, Black Sea.

1. INTRODUCTION

The Black Sea has coastlines in Turkey, Russia, Ukraine, Romania, Bulgaria and Georgia, and is contained by these coastlines, with access to the open sea available through the Straits of Istanbul and Canakkale. These straits are very busy waterways, with 42553 ships having entered or exited the Black Sea in 2016 (DTGM, 2017). In addition to this number, it can be seen that the Black Sea has a vessel density that cannot be underestimated when one also considers the traffic of fishing vessels and the volume of ships that only operate within the confines of the Black Sea. Accidents that have occurred in the Black Sea threaten not only safety of life and property but also the environment and marine ecosystem.

Marine accidents, especially in terms of sinking, grounding and collision-contact, have always been a major concern. Many accident analysis studies have been conducted in literature in order to understand the causes of these accidents and to prevent them from occurring in the future. In light of these studies the main causes of collision-contact accidents can be listed as: violation of International Regulations for Preventing Collisions at Sea (COLREG), inappropriate lookout, ineffective use of bridge navigation equipment, poor visibility, heavy traffic, darkness, and communication and coordination errors between vessels and bridge team members (Kujala et al., 2009, Montewka et al., 2012, Chauvin et al., 2013, Uğurlu et al., 2015b, Uğurlu et al., 2015c, Yıldırım et al., 2017). Similarly, some identified causes of grounding accidents include: improper passage planning, position fixing errors, interpretation error of conning officer, lack of coordination and communication of bridge team members, inappropriate chart usage, fatigue, and heavy weather and sea conditions (Mullai and Paulsson, 2011, Uğurlu et al., 2015b, Uğurlu et al., 2015c, Uğurlu et al., 2015d, Yıldırım et al., 2017). Finally, in the literature, the number of accident analysis studies relating to sinking accidents appears to be less than the number relating to groundings, and collision-contact accidents. However, it is possible to identify some of the main factors that contribute to sinking accidents as; improper cargo stowage and ship stability, deformed hull structure, and heavy weather and sea conditions (Soares and Teixeira, 2001, Uğurlu et al., 2015a).

Accident analysis studies, based on accident investigations, make it possible to understand the causes of an event or accident, in order to prevent the occurrence of such accidents and to provide improved safety (Doytchev and Szwillus, 2009, Uğurlu et al., 2015a). Several analytical and evaluation methods have been developed to analyse accident data to further improve maritime safety. These include Event Tree Analysis (ETA), Fault Tree Analysis (FTA), The Decision-Making Trial and Evaluation Laboratory (DEMATEL), Analytical Hierarchy Process (AHP), Geographic Information System (GIS) (Uğurlu and Yıldız, 2016), Fuzzy-AHP, Human Factor Analysis and Classification System (HFACS) and Bayesian Network (BN) (Sklet, 2004, Trucco et al., 2008, Matellini et al., 2013, Mentes et al., 2015, Uğurlu et al., 2015b). In this study, HFACS models whose reliability has been proven by many studies are used to analyse marine accidents that have occurred in the Black Sea (Shappell and

Wiegmann, 2004; Wiegmann et al., 2005) and BN (Guikema and Goffelt, 2008; Jones et al., 2010; Cai et al., 2013).

2. BACKGROUND

2.1. HFACS

In the Swiss cheese model, accidents are defined as occurrences that cause undesirable consequences, resulting from discrepancies and disturbances between the components of the system (Reason et al., 1990). In the Swiss cheese model, the events that caused the accident are defined on four levels and these four levels are grouped under two main headings; latent factors and active failures. The first three levels represent latent factors and the last level represents active failures. According to this model, there are hidden (latent) factors behind visible (active) failures within an accident, as shown in Figure 1 (Reason et al., 2006).

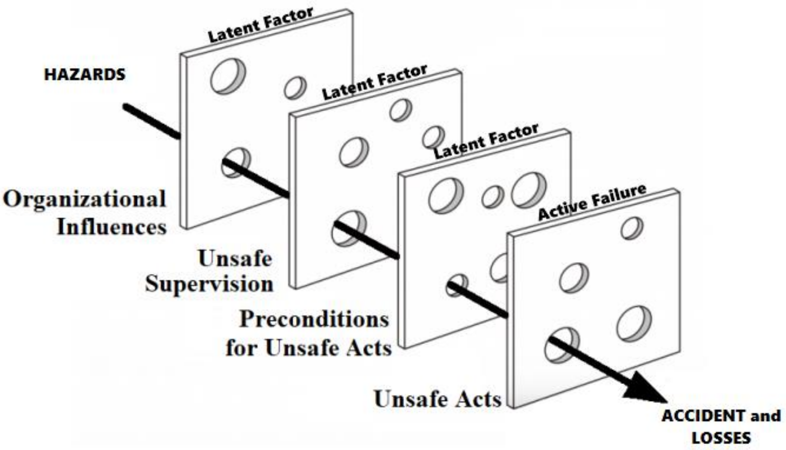

Figure 1. Swiss cheese model

According to Reason’s model, accidents occur because of deficiencies in the first three levels paving the way for unsafe acts in the fourth level, i.e., the unsafe acts and behaviours of operators. Latent factors in the system are often unnoticed until the accident occurs. The Human Factors Analysis and Classification System HFACS is a hybrid method, containing human factors and system approaches, as well as integrating Reason's Swiss Cheese model (Reason, 2000; Shappell and Wiegmann, 2000; Uğurlu et al., 2018). HFACS is a useful tool for analysing the effects of human error on devastating events, accidents, dangerous events, and deficiencies in different sectors (Patterson, 2008, Baysari et al., 2008, Patterson and Shappell, 2010, Lenne et al., 2012, Chauvin et al., 2013, Chen et al., 2013, Zhan et al., 2017, Theophilus et al., 2017, Uğurlu et al., 2018).

In many studies carried out with HFACS, revisions were needed within the main structure. In studies conducted by many researchers such as Reinach and Viale (2006), Chen et al., (2013) and Chauvin et al., (2013), changes were made to the main HFACS structure and the structure was adapted to the stated field of application. The latest change in the HFACS structure for the analysis of marine accidents was made by Uğurlu et al., (2018). In their research, the HFACS structure was modified to make it more suitable for analysis of marine accidents by revising the main categories and sub-categories in their study.

In this structure (Uğurlu et al., 2018), the operational conditions (environmental factors) level has been added to the main HFACS structure and evaluated as the last step in the occurrence of marine accidents. Operational conditions include internal (e.g. rudder failure) and external (e.g. restricted visibility) factors that are closely related to the accident, but which cannot be prevented directly by the ship's personnel. For marine accidents that have occurred in the Black Sea and considering the occurrence of the accidents, it would not be appropriate to examine the operational conditions under pre-conditions for unsafe acts. Therefore, operational conditions are not considered as pre-conditions for unsafe acts in accident occurrence, they are to be considered as top-level events. In other words, even if the necessary conditions for the accident occur simultaneously, an accident will not occur unless the appropriate operational conditions occur. From past to the present, in none of the HFACS structures have the accident occurrences been evaluated in this way. For the reasons mentioned above, the new HFACS structure for Passenger Vessels (HFACS-PV) is the most accurate way to describe marine accidents. Therefore, in this study, the new HFACS structure is deemed suitable for the analysis of marine accidents in the Black Sea. The HFACS structure applied in this paper is shown in Figure 2 (Uğurlu et al., 2018).

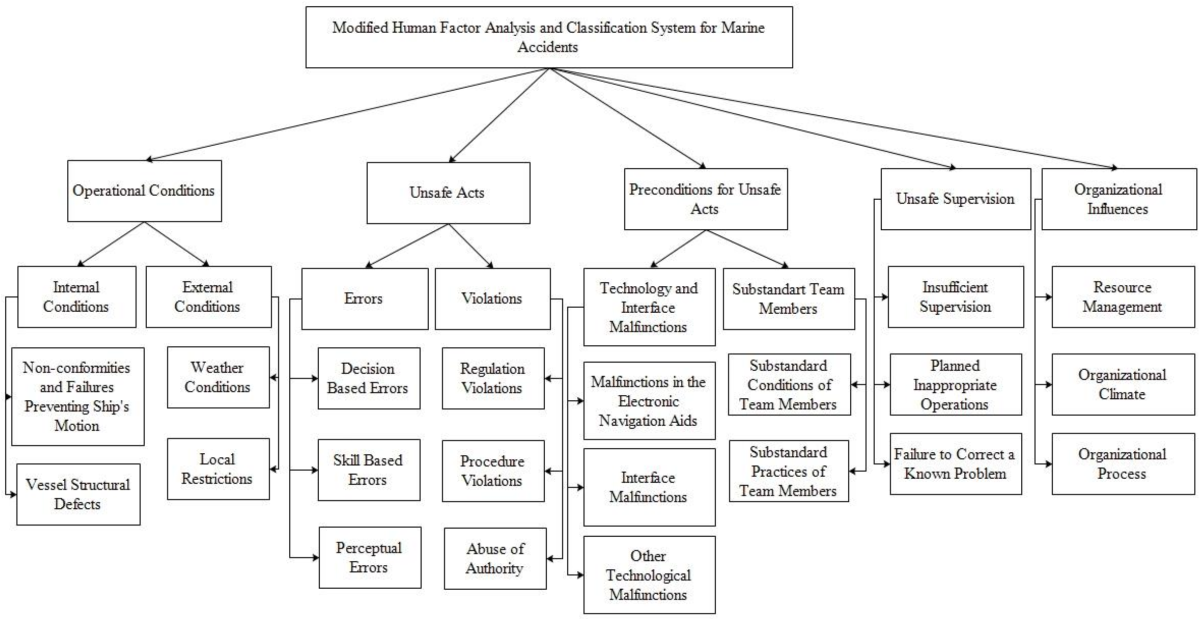

Figure 2. General framework of HFACS structure used in this study

2.2. Bayesian Networks

Bayes' theorem is a conditional probabilistic approach arising from the concept of subjective probability. The Bayesian model or the probabilistic Directed Acyclic Graph (DAG) model yields a network model (Bearfield and Marsh, 2005, Hänninen, 2008, Brooker, 2011, Pristrom et al., 2016). In other words, BN models express a network model with a set of variables that have conditional dependencies among each other. When constructing a BN, it is important to note that the number of permutations in the Conditional Probability Tables (CPTs) increases exponentially with the number of parent nodes and the number of states in the CPT. Similarly, the total number of cells in a CPT is equal to the product of the possible number of states in the node and the number of combinations of parental states (Cai et al., 2014; Fenton and Neil, 2013; Loughney and Wang, 2017).

Conditional probabilities are essential to BNs and they can be expressed by statements such as "B occurs given that A has already occurred" and "given event A, the probability of event B is 'p'", which is denoted by $P(B|A) = p$. This specifically means that if event A occurs and everything else is unrelated to event B (except event A), then the probability of B is 'p' (Eleye-Datubo et al., 2006, Matellini et al., 2013, Fenton and Neil, 2013, Pristrom et al., 2016). Conditional probabilities are part of the joint probability of the intersection of A and B, $P(A \cap B)$, and can be shown as:

$$P(A \,\big|\, B) = \; P(A \cap B)/P(A) \tag{2}$$

For any two events A and B:

$$P(A \cap B) = P(B|A) \times P(B) = P(A|B) \times P(A) \tag{3}$$

It should be noted that if $P(A) = 0$, then A is an event with no possible outcomes. Therefore, it follows that $A \cap B$ also contains no possible outcomes and $P(A \cap B) = 0$. The independence of events can be shown by definition. Let A and B be any events with $P(A) \neq 0$ then A and B can be defined through Equation 4:

$$P(B) = P(B|A) \tag{4}$$

Similarly, from Equation 4 one can define Equation 5:

$$P(A \cap B) = P(A) \times P(B) \tag{5}$$

All of these possibilities are specified in the CPTs by evaluating the relevant parent nodes for each child node. If the node is not a child node, then the initial probability values are specified in the Non-Conditional Probability Table (NCPT) (Pristrom et al., 2016). Determining the probabilities of parent nodes, root nodes and child nodes is very important for the results of the study (Li et al., 2014, Pristrom et al., 2016).

3. METHODOLOGY

This study is an accident analysis that examines marine accidents that have occurred in the Black Sea, over the past 20 years. In this context, a total of 5,655 marine accidents recorded in Global Integrated Shipping Information System (GISIS) were scrutinized, and a total of 109 accidents were deemed to have occurred in the Black Sea. In this study, only grounding, sinking, collision-contact accidents were investigated (89 of 109 accidents). This is the first study that analyses the accidents that have occurred in the entire Black Sea area as a collective. This study is aims to provide information to the maritime industry regarding marine accidents that have occurred in the Black Sea in order to mitigate against the occurrence of similar accidents in the future. The flow chart in Figure 3 summarizes the stages of this study. The steps of the methodology in this study are outlined as follows:

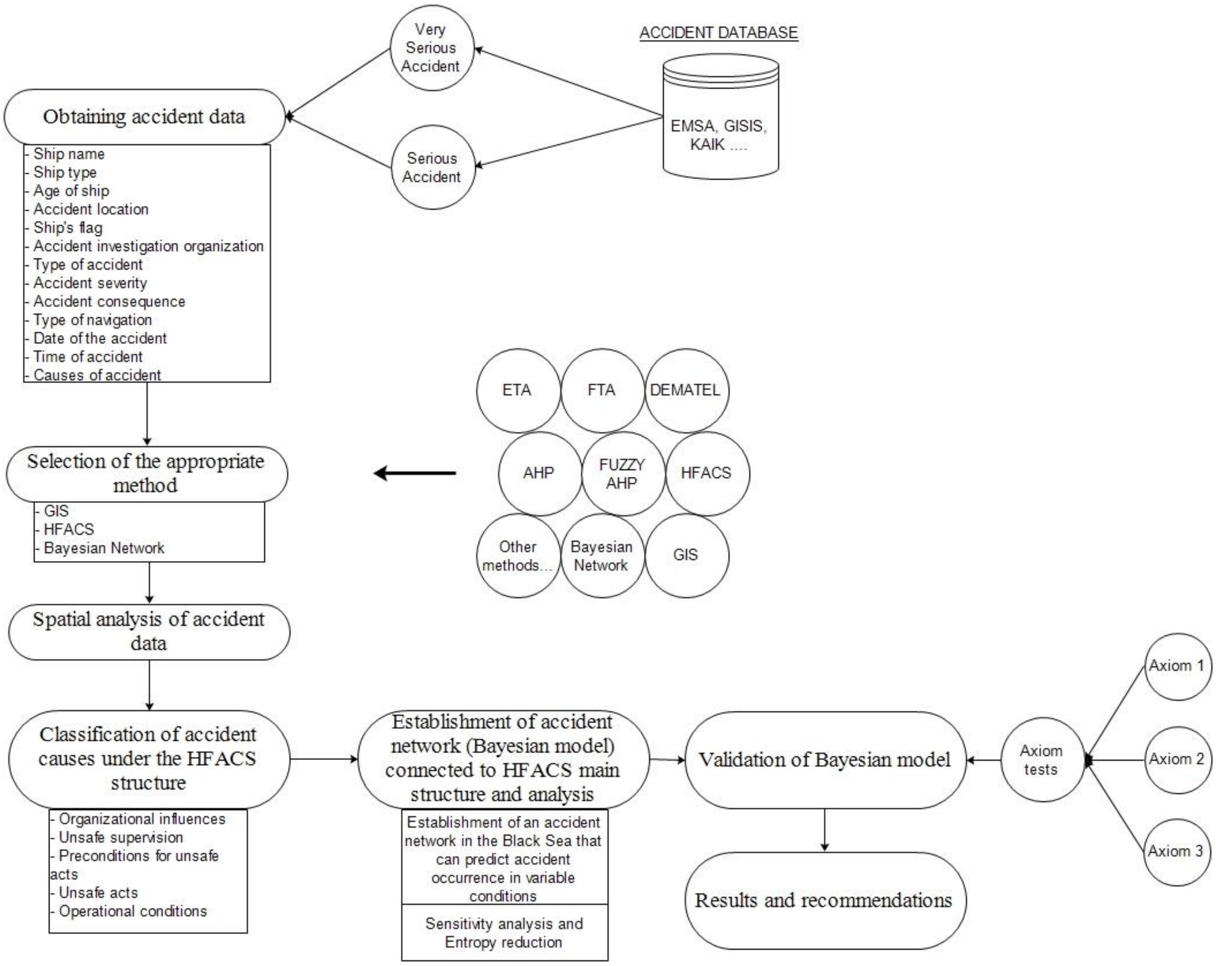

Figure 3. Flow chart of the study

Step 1 – Gathering the accident data and choosing the appropriate method for accident analysis: The dataset of this study is limited to serious and very serious accidents that have occurred in the Black Sea. A very serious marine casualty involves the total loss of the ship or a death or severe damage to the environment (IMO, 2008). A serious marine casualty results in immobilization of main engines, extensive accommodation damage, severe structural damage, rendering the ship unfit to proceed, pollution or a breakdown necessitating towage or shore assistance (MAIB, 2013).

Accident reports recorded in GISIS, European Maritime Safety Agency (EMSA), Accident Investigation Board (Turkey), Maritime Accident Investigation Bureau (Georgia), Marine Accidents Investigation Department (Romania), Maritime and Railway Accident Investigation (Bulgaria) and Lloyd's Register databases are used to obtain detailed information about these accidents. By scrutinizing these databases, a new database is created by using Microsoft Excel, where there are many items such as accident type, ship type, gross tonnage, ship size, accident coordinates, and date and time of the accident. With the new database created, examination and interpretation of the accidents have become easier.

An appropriate method is chosen for both qualitative and quantitative analysis of accidents in the Black Sea by taking into account accident reports, accident analysis studies, and qualitative and analytical models used in accident analysis. In order to analyse accident reasons in the Black Sea, HFACS (qualitative) and BN (both qualitative and quantitative) methods, which are widely used in many accident analysis studies, have been chosen.

Step 2 – Spatial analysis of accident data: ArcGIS 10.3 is used for spatial analysis of accidents in the Black Sea. Firstly, accident coordinates in the MS Excel GIS database are digitized. Secondly, digitized accident coordinates and accident information were transferred to ArcGIS 10.3. Thirdly, the marine accident data is overlaid on a map of the Black Sea and evaluated. In this stage, accidents that have occurred in the Black Sea are analysed by spatial density analysis (kernel density estimation) using ArcGIS 10.3. In this regard, hot spots where marine accidents have occurred, have been identified to determine the high-risk areas of the Black Sea, in terms of navigation.

Step 3 – Identification of accident reasons and classification under the HFACS structure: In order to better understand and interpret the occurrence of marine accidents, accident factors are classified under a new HFACS structure (Uğurlu et al., 2018). HFACS is considered one of the best hybrid methods, containing human factors and system approaches, as well as integrating Reason's Swiss Cheese model (Shappell and Wiegmann, 2004; Chauvin et al., 2013; Uğurlu et al., 2018). This allows for accident causes to be conceptualized as interactions among active and latent system failures.

Step 4 – Creating the BN based on main HFACS structure and analysis: In this step of the study, the BN structure is formed, depending on the HFACS framework created in the previous step. The relationship between the nodes in the BN has been established by considering accident reports and occurrence of accidents. In the next step, CPTs are created by using the information in the accident database which is created in the study. Once the relevant nodes and CPTs are identified, they are input into a BN software package, HuginResearcher 7.7 (Hugin, 2018). The network is reviewed to ensure that there are no missing factors.

Hugin software is used to run the model and test for conflicts in data by inserting evidence (probabilities) in various nodes. This step involves the application of sensitivity analysis and entropy reduction. Sensitivity analysis assumes that input parameters to the model are not accurate; it shows the designer the variations in a systems reliability, given some variation of the input parameters values (Cai et al., 2013; Cai et al., 2019). Entropy reduction is applied to the likelihood of accident categories, and the changes in the involved child nodes and parent nodes are evaluated (Cai et al., 2013; Yang et al., 2009). The purpose of entropy reduction is to determine which nodes will be utilized in the sensitivity analysis, for each HFACS level. Sensitivity analysis reveals the most likely accident combinations and probability values, as well as determining the influence of the most effective active and latent failures under each HFACS level for all accident categories. At this stage of the study, an accident network summarizing the occurrence of accidents in the Black Sea has been developed. The accident network allows users to estimate the risk of an accident occurring on the Black Sea given a variety of factors (weather conditions, vessel's structure, navigation area, unsafe acts, preconditions for unsafe acts). As a result, the key factors that cause accidents can be identified and prioritized in order to assist with accident mitigation.

Step 5 – Validation of the BN Model: Validation is the key aspect of the methodology as it provides a reasonable amount of confidence in the results of the model. In current work and literature, there is a three-axiom based validation procedure, which is used for partial validation of a proposed BN model. The three axioms to be satisfied are given as follows (Jones et al., 2009, Pristrom et al., 2016):

- Axiom 1: A small increase or decrease in the prior subjective probabilities of each parent node should certainly result in the effect of a relative increase or decrease of the posterior probabilities of the child node.
- Axiom 2: Given the variation of subjective probability distributions of each parent node, its influence magnitude to the child node should be kept consistent.
- Axiom 3: The total influence magnitudes of the combination of the probability variations from “x” attributes (evidence) on the values should always be greater than that from the set of “x-y” ($y \epsilon x$) attributes.

4. TEST CASE

The example of the TOLSTOY accident, used as a test case, explains how the HFACS and BN structures are constructed for each accident by adhering to the research methodology. For the TOLSTOY accident, as with each accident in the dataset of the study a HFACS and BN structure was formed. Eventually all BNs were overlapped and a final BN structure was formed containing all accident data.

Step 1 – Gathering the accident data and choosing the appropriate method for accident analysis: The Tolstoy vessel sinking accident took place in September 2008 (MTITC, 2009); she commenced to navigation from Rostov-Don port (Russia) to Nemrut port (Turkey) with scrap metal cargo on 22/09/2008. After passing the Kerch channel on 24/09/2008, she was exposed to heavy weather and sea conditions in the Black Sea and sank off Varna. For the purpose of the study, the accident report was examined, and the key accident data is presented in Table 1.

Table 1. TOLSTOY accident data

Name of the ship	Gross/ length over all	Type of the accident	Accident position	Accident area	Age of the vessel	River type vessel	Type of vessel	Date of accident	Consequence
Tolstoy	3994 / 138,5m	Sinking	42°44’39.2N - 028°11’29.5E	Coastal water	38	Yes	Bulk Carrier	27.09.2008	Total loss of ship, loss of life

Step 2 - Spatial analysis of accident data: The position data of the Tolstoy accident was placed on the Black Sea map with ArcGIS 10.3, as shown in Figure 4.

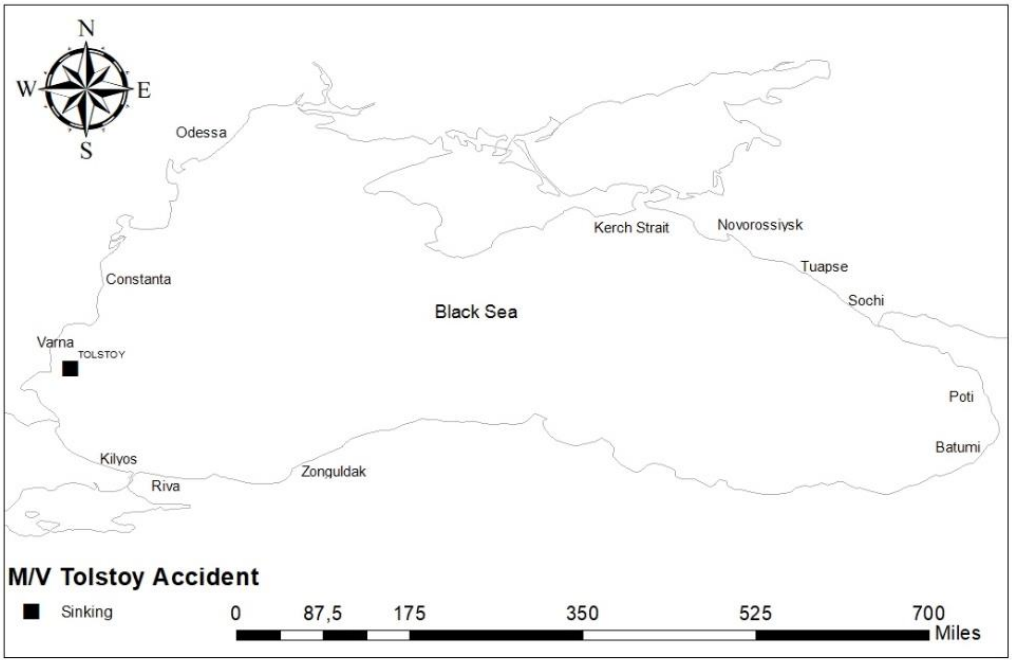

Figure 4. Position of TOLSTOY accident on Black Sea map

Step 3 – Classification of factors under HFACS structure: Based on the TOLSTOY accident report, latent and active failures that cause accidents are classified under the HFACS structure.

- Operational conditions: Heavy weather and sea conditions (external condition/weather condition), coastal water (external condition/local restriction), old vessel structure (internal condition/vessel structural defects), inland vessel (internal condition/vessel structural defects) and engine failure (internal condition/non-conformities and failures preventing ship`s motion).

- Unsafe acts: Navigation on storm (errors/decision-based error), inappropriate stability (violations/regulation violation) and use of vessel within limits of design conditions (violations/regulation violation).
- Pre-conditions for unsafe acts: Fatigue (substandard team members/substandard conditions of team members), lack of situational awareness (substandard team members/substandard conditions of team members), lack of internal and external communication (substandard team members/substandard practices of team members), mismanagement of port operation (substandard team members/substandard practices of team members) and mismanagement of vessel navigation operation (substandard team members/substandard practices of team members).
- Unsafe supervision: Inadequate manning (inappropriate planned operations), faulty port cargo operation planning (inappropriate planned operations), inappropriate vessel cargo operation planning (inappropriate planned operations) and lack of planned maintenance (insufficient supervision).
- Organizational influences: Minimum safe manning strategy (organizational climate/organizational culture), unqualified crew assignment (resource management/human resource), lack of training and familiarisation to inland vessel structure (resource management/human resource) and not according to norm in the oversight and control mechanism (organizational process/oversight).

Step 4 – Creating the BN based on main HFACS structure and analysis: In view of the accident report and the occurrence of the accident, a BN was established depending on the HFACS structure. The BN structure for the TOLSTOY accident is presented in Figure 5.

Figure 5. BN structure for TOLSTOY accident

4.1. Conditional Probability Calculations

The formulation of the CPT of the child node “Vessel Navigation Operation Planning” (Safe/Unsafe) shall be used an example to demonstrate the general formulation of the CPTs in the BN. This node has 3 parent nodes: “Training and Familiarization” (Sufficient/Insufficient), “Oversight and Control” (Adequate/Inadequate) and “Port or Company Pressure” (No/Yes). The safe or unsafe state of the "Vessel Navigation Operation Planning" node change depending on the three nodes (Figure 6).

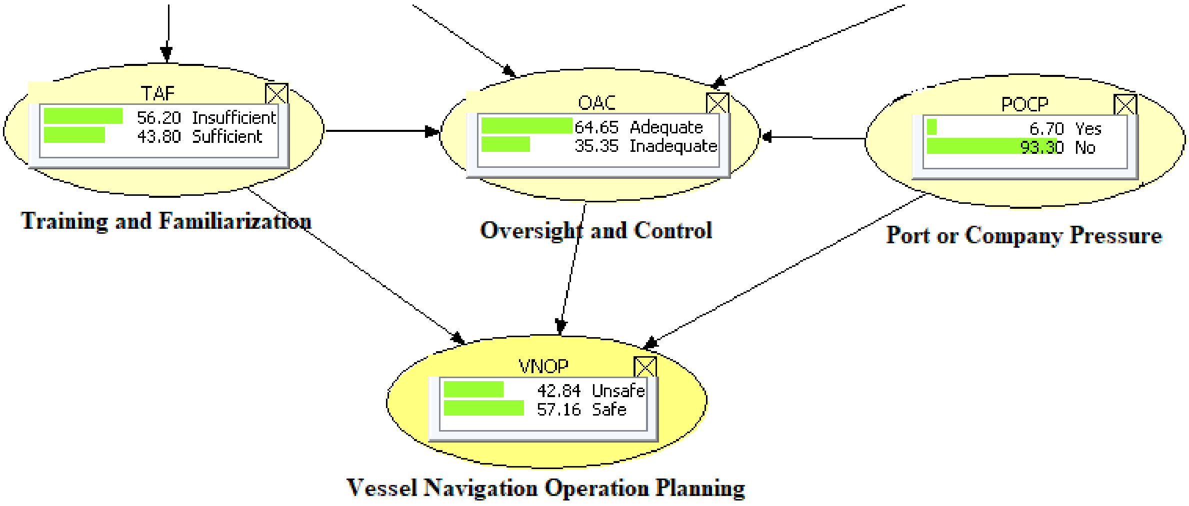

Figure 6. Bayesian network structure for the “Vessel Navigation Operation Planning’’ node

The “Port or Company Pressure” node is only the root node. The calculation of initial probability values based on the accident reports of the "Port or Company Pressure" node is presented below.

It was observed that 6 of the total 89 accidents, in the Black Sea, involved "port or company pressure". Therefore, the initial probability value for the “Yes” state of the “Port or Company Pressure” node is calculated as 6/89 = 6.7%. The probability value for the “No” state is 1-0.06.7 = 93.3% (Figure 6). Furthermore, marginal probability value for the "insufficient" state of the "Training and familiarization" node is 56.20%, and the posterior probability value for the "inadequate" state of the “Oversight and Control” node is 35.35%.

Table 2. Conditional probability table for “Vessel Navigation Operation Planning” node

	Port or Company Pressure	Yes				No			
	Oversight and Control	Adequate		Inadequate		Adequate		Inadequate	
	Training and Familiarization	Insufficient	Sufficient	Insufficient	Sufficient	Insufficient	Sufficient	Insufficient	Sufficient
Vessel Navigation Operation Planning	Unsafe	0.7	0.5	1	1	0.333	0	1	0.485
	Safe	0.3	0.5	0	0	0.667	1	0	0.515

According to the Bayesian network created in the study, there are 8 parental combinations in which "Vessel Navigation Operation Planning” is positive or negative. The conditional probability values for these 8 combinations are presented in Table 2. Based on these conditions, the marginal probability value for the state "safe" of the "Vessel Navigation Operation

Planning” node was calculated as 57.16% and the posterior probability value for the "unsafe" state is 42.84%.

According to Equations 2 and 3, the probability of the "Vessel Navigation Operation Planning” node to be in the state “unsafe” is calculated as follows (Vessel Navigation Operation Planning: VNOP, Training and Familiarization: TAF, Oversight and Control: OAC, Port or Company Pressure: POCP):

$$
\begin{aligned}
P(\text{VNOP(Unsafe)}) = {} & [(P(\text{VNOP(Unsafe)}|\text{POCP(Yes), OAC(Adequate), TAF(Insufficient)}) \times \\
& P(\text{POCP(Yes)}) \times \text{OAC(Adequate)} \times \text{TAF(Insufficient)}] + \\
& [(\text{VNOP(Unsafe)}|\text{POCP(Yes), AC(Adequate), TAF(Sufficient)}) \times \\
& P(\text{POCP(Yes)} \times \text{OAC(Adequate)} \times \text{TAF(Sufficient)}] + \\
& [(P(\text{VNOP(Unsafe)}|\text{POCP(Yes), OAC(Inadequate), TAF(Insufficient)}) \times \\
& (\text{POCP(Yes)}) \times \text{OAC(Inadequate)} \times \text{TAF(Insufficient)}] + \\
& [(P(\text{VNOP(Unsafe)}|\text{POCP(Yes), OAC(Inadequate), TAF(Sufficient)}) \times \\
& P(\text{POCP(Yes)}) \times \text{OAC(Inadequate)} \times \text{TAF(Sufficient)}] + \\
& [(P(\text{VNOP(Unsafe)}|\text{POCP(No), OAC(Adequate), TAF(Insufficient)}) \times \\
& P(\text{POCP(No)}) \times \text{OAC(Adequate)} \times \text{TAF(Insufficient)}] + \\
& [(\text{VNOP(Unsafe)}|\text{POCP(No), OAC(Adequate), TAF(Sufficient)}) \times \\
& P(\text{POCP(No)} \times \text{OAC(Adequate)} \times \text{TAF(Sufficient)}] + \\
& [(P(\text{VNOP(Unsafe)}|\text{POCP(No), OAC(Inadequate), TAF(Insufficient)}) \times \\
& (\text{POCP(No)}) \times \text{OAC(Inadequate)} \times \text{TAF(Insufficient)}] + \\
& [(P(\text{VNOP(Unsafe)}|\text{POCP(No), OAC(Inadequate), TAF(Sufficient)}) \times \\
& P(\text{POCP(No)}) \times \text{OAC(Inadequate)} \times \text{TAF(Sufficient)}]
\end{aligned}
$$

$$
\begin{aligned}
P(\text{VNOP(Unsafe)}) = {} & (0.7 \times 0.067 \times 0.6465 \times 0.5620) + (0.5 \times 0.067 \times 0.6465 \times 0.4380) + \\
& (1 \times 0.067 \times 0.3535 \times 0.5620) + (1 \times 0.067 \times 0.3535 \times 0.4380) + \\
& (0.333 \times 0.933 \times 0.6465 \times 0.5620) + (0 \times 0.933 \times 0.6465 \times 0.4380) + \\
& (1 \times 0.933 \times 0.3535 \times 0.562) + (0.485 \times 0.933 \times 0.3535 \times 0.438) \\
& = 0.4284\ (24.84\%)
\end{aligned}
$$

Probability of “safe” state of “Vessel Navigation Operation Planning” node calculated as:

$$=1-0.4284 = 0.5716\ (57.16\%)$$

4.2. Marine Accidents on the Black Sea

Of the 109 accidents in the Black Sea 37 were due to sinking, 32 were due to grounding and 20 were due to collision-contact as shown in Table 3. In the past 20 years there have been a total of 23 fatal accidents where 149 people have lost their lives. Furthermore, within these fatal accidents there have been 54 vessels lost and 12 cases of marine pollution reported. Given the gathered data, sinking and grounding accidents are more concentrated in coastal waters and anchorage areas. On the other hand, collision-contact accidents are more concentrated in ports and open seas. From the data it can also be stated that sinking and grounding accidents occur more frequently (70.2% sinking, 87.5% grounding) in autumn and winter (6 months between October and March). However, this seasonal trend is not apparent for collision-contact accidents. Continually, 86% of sinking accidents, 78.1% of grounding accidents and 55% of collision-contact accidents have involved ships over 20 years old. The average age of the vessels involved in sinking accidents is approximately 29.5 years, while the average age of the vessels involved in grounding accidents was 26.8 years. Finally, a total of 37.7% of sinking and grounding accidents involved inland waterway vessels operating in the Black Sea.

Table 3. Distribution of marine accidents occurred in the Black Sea

	Sinking	Grounding	Collision-Contact
Total number of accidents	37	32	20
Total number of fatal accidents	16	3	4
Total number of deaths	128	8	13
Total number of vessels lost	37	9	8
Total number of reported pollutions	7	4	1
Sea area where accidents occurred			
Anchorage	11	13	2
Port area (Except Anchorage)	4	7	8
Coastal waters (<12ˈ)	13	12	4
Open sea	8	-	6
Month of the accident occurred			
January	8	3	1
February	6	9	4
March	2	5	2
April	1	1	5
May	2	-	2
June	2	-	-
July	2	-	3
August	-	-	-
September	4	3	1
October	3	1	-
November	5	5	1
December	2	5	1
Age of the vessel			
0-10	4	4	3
11-20	1	3	6
>20	32	25	11

Average age of vessels	29.5	26.8	21.3
Average age of river type vessels	35.6	25	30
Number of river type vessels	14	12	5

5. BAYESIAN THEORY AND BAYESIAN NETWORK STRUCTURE

5.1. Occurrence of BN Developed from Main HFACS Structure

The main structure and sub-elements of the HFACS structure that has been formed for this study, for the accidents that fall under the very serious and serious categories are presented in Figure 7. The BN which has been constructed on the basis of the main HFACS structure is shown in Figure 8. Similarly, the abbreviations used in BN structure are presented in Table 4.

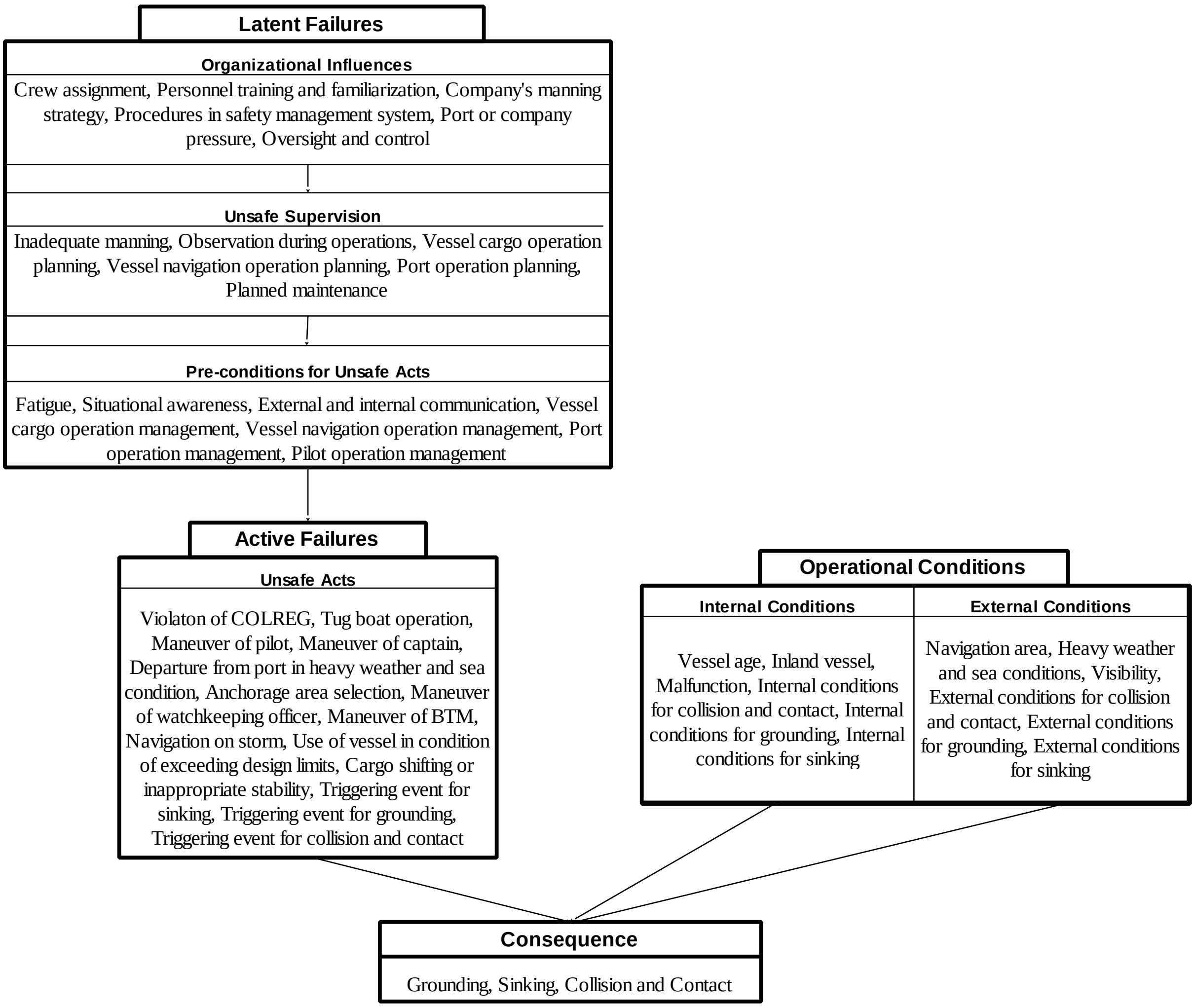

Figure 7. Main structure and sub-elements of HFACS developed for this study

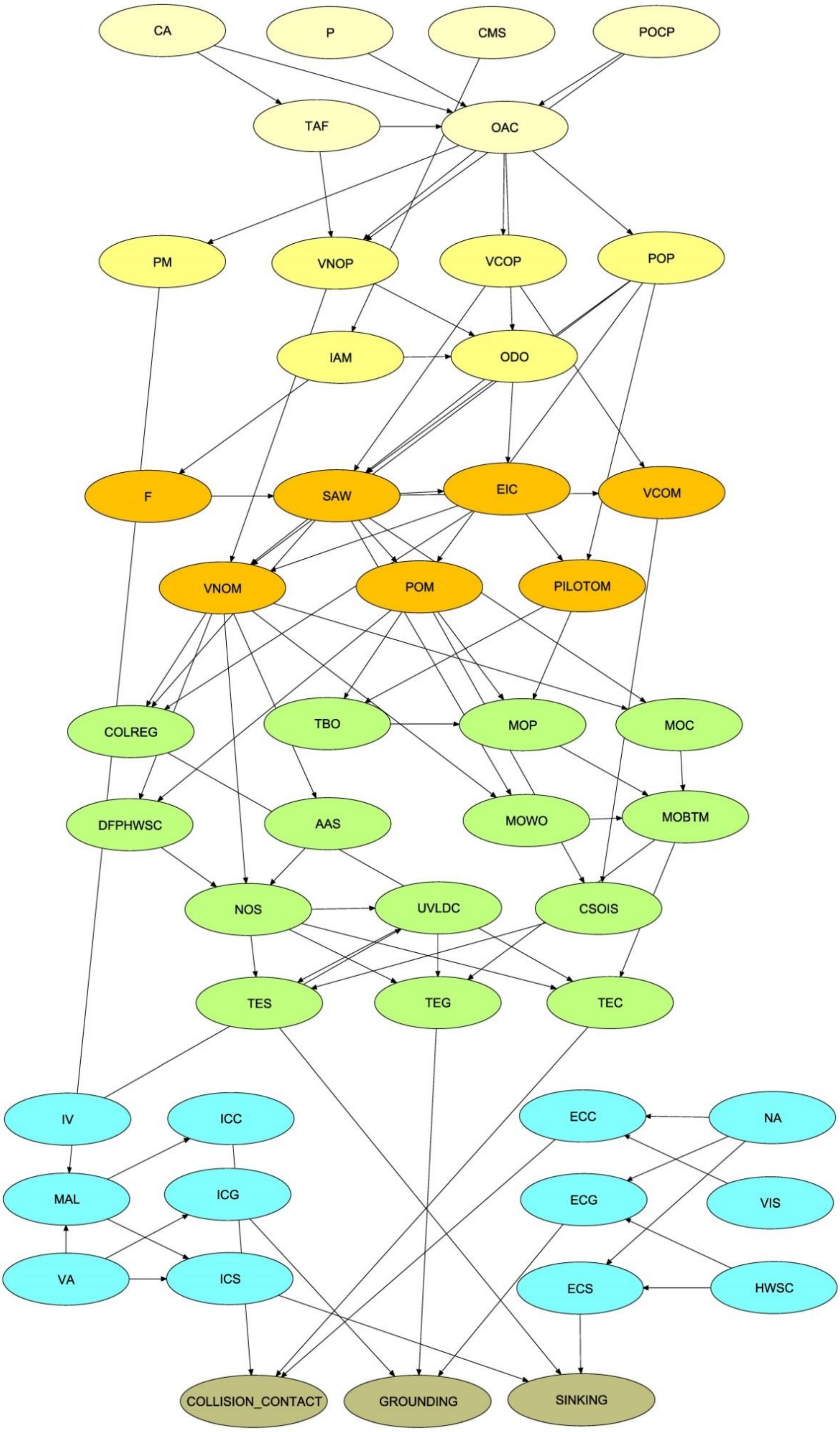

Figure 8. BN model for collision-contact, grounding and sinking occurring in the Black Sea

Table 4. Abbreviations used in BN structure

Failures	Abbreviation
Crew Assignment	CA
Procedure	P
Company’s Manning Strategy	CMS
Port or Company Pressure	POCP
Training and Familiarization	TAF
Oversight and Control	OAC
Inadequate Manning	IAM
Observation During Operation	ODO
Vessel Cargo Operation Planning	VCOP
Vessel Navigation Operation Planning	VNOP
Port Operation Planning	POP
Planned Maintenance	PM
Fatigue	F
Situational Awareness	SAW
External and Internal Communication	EIC
Vessel Cargo Operation Management	VCOM
Vessel Navigation Operation Management	VNOM
Port Operation Management	POM
Pilot Operation Management	PILOTOM
International Regulations for Preventing Collisions at Sea	COLREG
Tug Boat Operation	TBO
Manoeuvre of Pilot	MOP
Manoeuvre of Captain	MOC
Manoeuvre of Watch-keeping Officer	MOWO
Manoeuvre of Bridge Team Members (BTM)	MOBTM
Departure from Port in Heavy Weather and Sea Condition	DFPHWSC
Anchorage Area Selection	AAS
Navigation on Storm	NOS
Use of Vessel within Limits of Design Conditions	UVLDC
Cargo Shifting or Inappropriate Stability	CSOIS
Triggering Event for Sinking	TES
Triggering Event for Grounding	TEG
Triggering Event for Collision and Contact	TEC
Vessel Age	VA
Inland Vessel	IV
Malfunction	MAL
Internal Conditions for Collision	ICC
Internal Conditions for Grounding	ICG
Internal Conditions for Sinking	ICS
Navigation Area	NA
Visibility	VIS
Heavy Weather and Sea Conditions	HWSC
External Conditions for Collision	ECC
External Conditions for Grounding	ECG
External Conditions for Sinking	ECS

5.1.1. Latent Failures

5.1.1.1. Organizational influences. Organizational influence is the first level in the HFACS framework, and it forms the basis of accident occurrence (Wiegmann and Shappell, 2001). Organizational influence includes not according to norm made by top level managers such as, fleet managers, technical managers, operations managers and crew managers *etc*. Organizational influences lead to the formation of not according to norm under the unsafe supervision factor in the framework and negatively affect the other top-level factors. In the constructed BN, the nodes of crew assignment (States: “qualified crew/unqualified crew”), personnel training and familiarization (“sufficient/insufficient”), company manning strategy (“minimum safe manning/optimum safe manning”), procedures (“appropriate/inappropriate”), port or company pressure (“yes/no”) and oversight and control (“adequate/inadequate”) have been examined under this framework.

Table 5 shows the latent factors under this level, along with their abbreviations, probabilities, parent nodes and child nodes. Crew assignment, procedure, port or company pressure and company manning strategy are root nodes. For this reason, these nodes have no conditional probabilities. The prior probabilities of nodes under this level are given in Appendix Table A1. The probabilities in the appendix tables were determined based on the observing frequency of the relevant root node in the 89 accidents investigated. The root node, Procedure (P), was observed in the state “inappropriate” in 5 accidents and “appropriate” in 84 accidents. Therefore, the prior probability value of procedure in the state “inappropriate” is taken as 5/89=5.6% and procedure in the state “appropriate” is taken as 94.4%. The prior probability values of other root nodes are also determined in this way.

Table 5. BN structure of organizational influences

Latent failures	Abbreviation	Negative expression	Probability (%)	Parent nodes	Child nodes
Crew Assignment	CA	Unqualified Crew	49.40	Root node	TAF, OAC
Procedure	P	Inappropriate	5.60	Root node	OAC
Company’s Manning Strategy	CMS	Minimum safe manning	10.10	Root node	IAM
Port or Company Pressure	POCP	Yes	6.70	Root node	OAC, VNOP
Training and Familiarization	TAF	Insufficient	56.20	CA	OAC, VNOP
Oversight and Control	OAC	Inadequate	35.35	CA, TAF, P, POCP	PM, VNOP, VCOP, POP, ODO

5.1.1.2. Unsafe Supervision. Unsafe supervision examines the consequences of leadership, such as, management of staff resources, planning of operations and solving known problems (Patterson and Shappell, 2010). These factors directly affect the occurrence of non-conformities under the level of pre-conditions for unsafe acts. Nodes examined under this level are: inadequate manning ("yes/no"), observation during operation ("clear/unclear"), vessel cargo operation planning ("adequate/inadequate"), vessel navigation operation planning ("safe/unsafe"), port operation planning ("adequate/inadequate") and planned maintenance ("completed/uncompleted") system as shown in Table 6. The conditional probability tables of these nodes are given in Appendix Table A2.

Table 6. BN structure of unsafe supervision

Latent failures	Abbreviation	Negative expression	Probability (%)	Parent nodes	Child nodes
Inadequate Manning	IAM	Yes	10.10	CMS	ODO, F
Observation During Operation	ODO	Unclear	39.95	IAM, OAC, VNOP, VCOP	SAW, EIC,
Vessel Cargo Operation Planning	VCOP	Inadequate	3.89	OAC	ODO, SAW, VCOM
Vessel Navigation Operation Planning	VNOP	Unsafe	42.84	TAF, OAC, POCP	ODO, VNOM
Port Operation Planning	POP	Inadequate	10.64	OAC	SAW, VNOM, POM, PILOTOM
Planned Maintenance	PM	Uncompleted	1.45	OAC	MAL

While determining the conditional probability values for the “safe/unsafe” states of the Vessel Navigation Operation Planning (VNOP) node in Table A2, the frequencies of the occurrence of the parent nodes; Port or Company Pressure (POCP), Oversight and Control (OAC), Training and Familiarization (TAF), shown in Figure 9, were investigated. Table 7 shows the number of observations in total accidents for each condition. There are 3 accidents in the data set (POCP/“no”+OAC/“adequate”+TAF/“sufficient”) where all POC, OAC and TAF nodes are positive. None of these accidents had unsafe vessel navigation planning, therefore, the probability of VNOP was taken as 1.0 (100%) safe and 0.0 (0%) unsafe for this condition, as shown in Appendix Table A2.

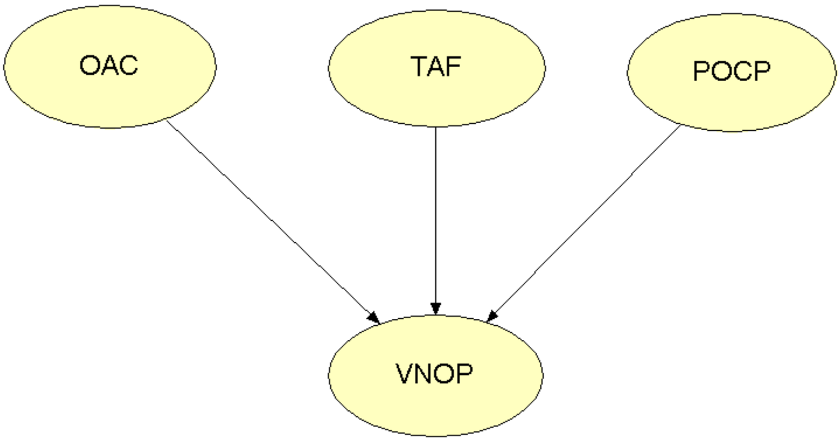

Figure 9. BN part of Vessel Navigation Operation Planning (VNOP) node

Table 7. Number of accidents observed for conditions of relevant nodes

	Port or Company Pressure	Yes (n=6)				No (n=83)			
	Oversight and Control	Adequate (n=2)		Inadequate (n=4)		Adequate (n=18)		Inadequate (n=65)	
	Training and Familiarization	Insufficient (n=0)	Sufficient (n=2)	Insufficient (n=3)	Sufficient (n=1)	Insufficient (n=15)	Sufficient (n=3)	Insufficient (n=13)	Sufficient (n=52)
Vessel Navigation Operation Planning	Unsafe	0	1	3	1	5	0	13	25
	Safe	0	1	0	0	10	3	0	27

*n = The number of accidents.

Based on the database, created in this study, there is 1 accident with the following conditions: “POCP/yes, OAC/inadequate, TAF/sufficient” and in this accident VNOP was observed as unsafe. Therefore, probability of VNOP was taken as 1.0 (100%) unsafe and 0.0 (0%) safe for this condition.

Similarly, there are 3 accidents with the following conditions: “POCP/no, OAC/inadequate, TAF/insufficient” and in all of these accidents, VNOP was observed as unsafe. Therefore, the probability of VNOP was taken as 1.0 (100%) unsafe and 0.0 (0%) safe for this condition (Appendix Table A2).

Furthermore, there are 15 accidents with the combination, “POCP/no, OAC/adequate, TAF/insufficient”. Five of these accidents are unsafely planned vessel navigation operations. Therefore, VNOP is taken as 5/15=0.333 unsafe and 0.667 safe for this condition (Appendix Table A2).

Continually, 52 accidents demonstrated the following combination: “POCP/no, OAC/inadequate, TAF/sufficient”. Twenty-five of these accidents showed unsafe plans for vessel navigation operations. Therefore, VNOP is taken as 25/52=0.485 unsafe and 0.515 (1-0.485) safe for this condition.

There is a conditional probability state where “POCP/yes, OAC/adequate and TAF/sufficient” was observed in 2 accidents. For only one of these accidents there is a “VNOP/unsafe condition”. Therefore, VNOP is taken as 1/2=0.5 unsafe and 0.5 safe for this condition. There were no accidents observed with the combination, “POCP/yes, OAC/adequate, TAF/insufficient”. However, in addition to the previous condition, the Training and Familiarization node is also negative in this condition. This increases the likelihood of an accident; therefore, a higher probability is expected. Therefore, VNOP for this condition is taken as 0.7 unsafe and 0.3 safe. All of the combinations outlined here can be seen in Appendix Table A2.

As stated in the previous example, all of the probabilities used in this study have followed the sequences in the accident data during the process of determining the conditional probabilities. All conditional probabilities, shown in other tables in the appendix, were determined through similar calculations.

5.1.1.3. Pre-condition for Unsafe Acts. The pre-condition for unsafe acts explains the operators' substandard conditions and the substandard practices (Li and Harris, 2006), and is the final stage in the HFACS structure that plays a role in the emergence of unsafe actions (the last stage of latent failures). The nodes that are examined under this level are: fatigue (“yes/no”), situational awareness (“sufficient/insufficient”), external and internal communication (“adequate/inadequate”), vessel cargo operation management (“safe/unsafe”), vessel navigation operation management (“safe/unsafe”), port operation management (“safe/unsafe”) and pilot operation management (“safe/unsafe”), as shown in Table 8. The CPTs of these nodes are given in Appendix Table A3.

Table 8. BN structure of pre-condition of unsafe acts

Latent failures	Abbreviation	Negative expression	Probability (%)	Parent nodes	Child nodes
Fatigue	F	Yes	1.12	IAM	SAW
Situational Awareness	SAW	Insufficient	39.10	F, VCOP, ODO, POP	EIC, VCOM, VNOM, POM, MOC, MOW/O, COLREG
External and Internal Communication	EIC	Inadequate	41.82	SAW, ODO	POM, VNOM, COLREG
Vessel Cargo Operation Management	VCOM	Unsafe	3.33	VCOP, SAW	CSOIS
Vessel Navigation Operation Management	VNOM	Unsafe	45.89	VNOP, SAW, POP, EIC	COLREG, DFPHWSC, NOS, AAS, MOW/O, MOC
Port Operation Management	POM	Unsafe	10.63	POP, SAW	MOP, CSOIS, TBO, DFPHWSC
Pilot Operation Management	PILOTOM	Unsafe	3.69	POP, EIC	MOP, TBO

5.1.2. Active Failures

5.1.2.1. Unsafe Acts. Unsafe acts are the visible causes of accidents and are the main focus of many researchers conducting accident analyses (Li and Harris, 2006). Many accident reports contain detailed information on these actions and focusing on these unsafe acts helps us to understand what has happened in the accident formulation. However, the conditions that cause unsafe acts are understood, it is possible to learn how and why an accident has happened, and it is also possible to take more constructive measures to prevent accidents from occurring in the future.

The nodes examined under the level of unsafe acts are: COLREG ("not-violated/violated"), tug boat operation ("operational/faulty"), manoeuvre of pilot ("appropriate/inappropriate"), manoeuvre of captain ("appropriate/inappropriate"), departure from port in heavy weather and sea condition ("no/yes"), anchorage area selection ("appropriate/inappropriate"), manoeuvre of watch-keeping officer ("appropriate/inappropriate"), manoeuvre of Bridge Team Members (BTM) ("appropriate/inappropriate"), navigation on storm ("no/yes"), use of vessel within limits of design conditions ("no/yes"), cargo shifting or inappropriate stability ("no/yes"), triggering event for sinking ("unobserved/observed"), and triggering event for grounding ("unobserved/observed"), triggering event for collision and contact ("unobserved/observed"). The outline of the nodes under unsafe acts is shown in Table 9 and the CPTs of these nodes are given in Appendix Table A4.

Table 9. BN structure of unsafe acts

Active failures	Abbreviation	Negative expression	Probability (%)	Parent nodes	Child nodes
COLREG	COLREG	Violated	38.75	VNOM, SAW, EIC	DFPHWSC, TEC
Tug Boat Operation	TBO	Faulty	4.76	POM, PILOTOM	MOP
Manoeuvre of Pilot	MOP	Inappropriate	4.14	TBO, POM, PILOTOM	MOBTM
Manoeuvre of Captain	MOC	Inappropriate	25.42	VNOM, SAW	MOBTM
Manoeuvre of Watchkeeping Officer	MOW/O	Inappropriate	8.32	VNOM, SAW	MOBTM
Manoeuvre of Bridge Team Members (BTM)	MOBTM	Inappropriate	31.21	MOP, MOC, MOW/O	TEG, TEC
Departure from Port in Heavy Weather and Sea Condition	DFPHWSC	Yes	4.46	VNOM, POM	NOS
Anchorage Area Selection	AAS	Inappropriate	8.95	VNOM	NOS
Navigation on Storm	NOS	Yes	32.68	VNOM, AAS, DFPHWSC	UVLDC, TES, TEC, TEG
Use of Vessel within Limits of Design Conditions	UVLDC	Yes	14.42	NOS, IV	TES, TEG
Cargo Shifting or Inappropriate Stability	CSOIS	Yes	5.08	VCOM, POM	TES
Triggering Event for Sinking	TES	Observed	26.10	NOS, UVLDC, CSOIS	SINKING
Triggering Event for Grounding	TEG	Observed	26.20	NOS, UVLDC, MOBTM	GROUNDING
Triggering Event for Collision and Contact	TEC	Observed	26.14	NOS, UVLDC, MOBTM	COLLISION AND CONTACT

5.1.3. Operational Conditions

Unsafe actions require events under operational conditions to occur in order for an accident to occur. Operational conditions are examined under two sub-categories, external and internal conditions. Nodes representing internal conditions are determined as: vessel age (“new/old”), inland vessel (“no/yes”), malfunction (“unobserved/observed”), internal operational conditions for collision (“unobserved/observed”), internal operational conditions for grounding (“unobserved/observed”) and internal operational conditions for sinking (“unobserved/observed”). In this study, ships that are 20 years old or more fall under the state “old” in the vessel age node.

External operational conditions include external factors that play a key role or are involved in accident occurrence. These factors have been categorized as: navigation area (“narrow water/port/anchorage/coastal water/open sea”), heavy weather and sea conditions (“no/yes”), visibility (“good/poor”), external operational conditions for collision (“unobserved/observed”), external operational conditions for grounding (“unobserved/observed”) and external operational conditions for sinking (“unobserved/observed”). The outline of the nodes under operational conditions is shown in Table 10. Vessel age, inland vessel, navigation area, visibility, heavy weather and sea conditions, in this BN, are all root nodes. The probability tables of these nodes are given in Appendix Table A5.

Table 10. Abbreviations, probabilities and parent and child nodes of operational conditions

Operational conditions	Abbreviation	Negative expression	Probability (%)	Parent nodes	Child nodes
Vessel Age	VA	Old	75.30	Root node	MAL, ICG, ICS
Inland Vessel	IV	Yes	34.80	Root node	UVLDC
Malfunction	MAL	Observed	4.82	PMS	ICC, ICS
Internal Conditions for Collision	ICC	Observed	21.76	MAL	COLLISION AND CONTACT
Internal Conditions for Grounding	ICG	Observed	35.94	VA	GROUNDING
Internal Conditions for Sinking	ICS	Observed	40.15	MAL, VA	SINKING
Navigation Area	NA	-	.	Root node	ECC, ECG, ECS
Narrow Waters		NW	14.6		
Port		PORT	19.1		
Coastal Waters		CW	25.8		
Open Sea		OS	13.5		
Anchorage		ANC	27.0		
Visibility	VIS	Poor	23.60	Root node	ECC
Heavy Weather and Sea Conditions	HWSC	Yes	79.80	Root node	ECG, ECS
External Conditions for Collision	ECC	Observed	7.46	NA, V	COLLISION AND CONTACT
External Conditions for Grounding	ECG	Observed	8.41	NA, HWSC	GROUNDING
External Conditions for Sinking	ECS	Observed	8.90	NA, HWSC	SINKING

5.1.4. Consequence Nodes

The final nodes added to the BN are the consequence nodes *i.e,* the accident events themselves. Accidents in this study are limited to collision-contact, grounding and sinking. The first four levels in the BN represent the formation of unsafe actions, and the 5th level represents the operational conditions. The separate levels in the BN are indicated by the colour changes in Figure 8 with Level 1 starting at the top.

There are three event sets that cause accidents for each accident category: unsafe act, internal operational condition and external operational condition. If an unsafe act comes together with the operational conditions (internal and external) necessary for accident occurrence, accident is inevitable. Therefore, each accident consists of at least one internal operational condition, at least one external operational condition, and at least one unsafe act. The conditional probability tables for the last stage of the BN are arranged according to this data and are demonstrated in Appendix Table A6.

6. RESULTS AND VALIDATION OF STUDY

To demonstrate some partial validation of the BN model, it must satisfy the three axioms outlined in the final step of the methodology. These axioms are to be analysed separately in the following sections.

6.1. Axiom 1

For validity of the BN to be established, it was first tested as to whether it fulfilled the requirements of Axiom 1. For this axiom, the changes in the posterior probabilities of the accident nodes (grounding, sinking and collision-contact) are observed given the changes in the prior probabilities of their parent nodes. Table 11 shows the changes of the posterior probabilities of the consequences given changes in the prior probabilities of the respective parent nodes.

In terms of grounding accidents, if an unsafe action occurs, the probability of grounding increases from 0.79% to 3.02%. If unsafe action does not occur, the accident simply does not occur. Furthermore, if bad external conditions are observed (bad weather and sea conditions), then the probability of grounding increases to 9.44%. However, if favourable external conditions are available (good weather conditions), the accident does not occur. Similarly, if internal conditions are observed, the probability of grounding increases to 2.21%, and if they are not observed, grounding will not occur.

Table 11 shows similar results for sinking and collision-contact accidents. Thus, this demonstrates that the BN model satisfies Axiom 1, as alterations made within the prior probabilities of the parent nodes, have a near-real impact on the posterior probabilities of the accident nodes.

Table 11. Test of Axiom 1 for each accident category

Condition	ICG Observed	Grounding Yes	ICS Observed	Sinking Yes	ICC Observed	Collision Contact Yes
Normal	35.94	0.79	40.15	0.94	21.76	0.43
Worst	100	2.21	100	2.35	100	1.96
Best	0	0	0	0	0	0
Condition	ECG Observed	Grounding Yes	ECS Observed	Sinking Yes	ECC Observed	Collision Contact Yes
Normal	8.41	0.79	8.90	0.94	7.46	0.43
Worst	100	9.44	100	10.59	100	5.71
Best	0	0	0	0	0	0
Condition	TEG Observed	Grounding Yes	TES Observed	Sinking Yes	TEC Observed	Collision Contact Yes
Normal	26.27	0.79	26.13	0.94	26.18	0.43
Worst	100	3.02	100	3.61	100	1.63
Best	0	0	0	0	0	0

6.2. Axiom 2

Axiom 2 states that given the variation of subjective probability distributions of each parent node, its influence magnitude to the child node should be kept consistent. Figure 10 shows the change in the posterior probabilities for the node ‘Grounding’ given changes made to the prior probabilities of its parent variables ‘Internal operational conditions for grounding’, ‘External operational conditions for grounding’ and ‘Triggering factor for grounding’. The general trend of the results indicates a proportional increase of the posterior probabilities given the increase in the individual prior probabilities. In other words, there is a consistent increase of probabilities for ‘Grounding=Yes’ due to the increase of probabilities of ‘Internal conditions for grounding=Observed’, ‘External conditions for grounding=Observed’ and ‘Triggering factor for grounding=Observed’. A similar observation can be made when analysing the node of ‘Sinking’ and ‘Collision-contact’ in Figure 11 and Figure 12. Given the information presented, it can be stated that the BN model satisfies Axiom 2.

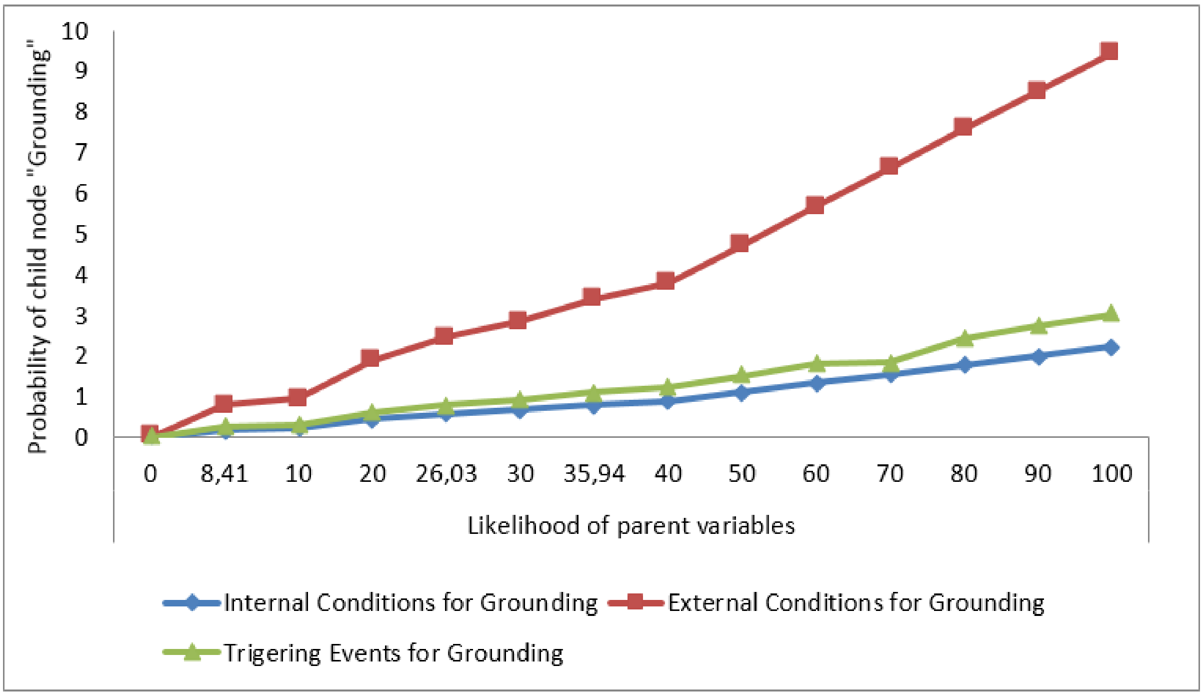

Figure 10. Change of probabilities for the node ‘Grounding’

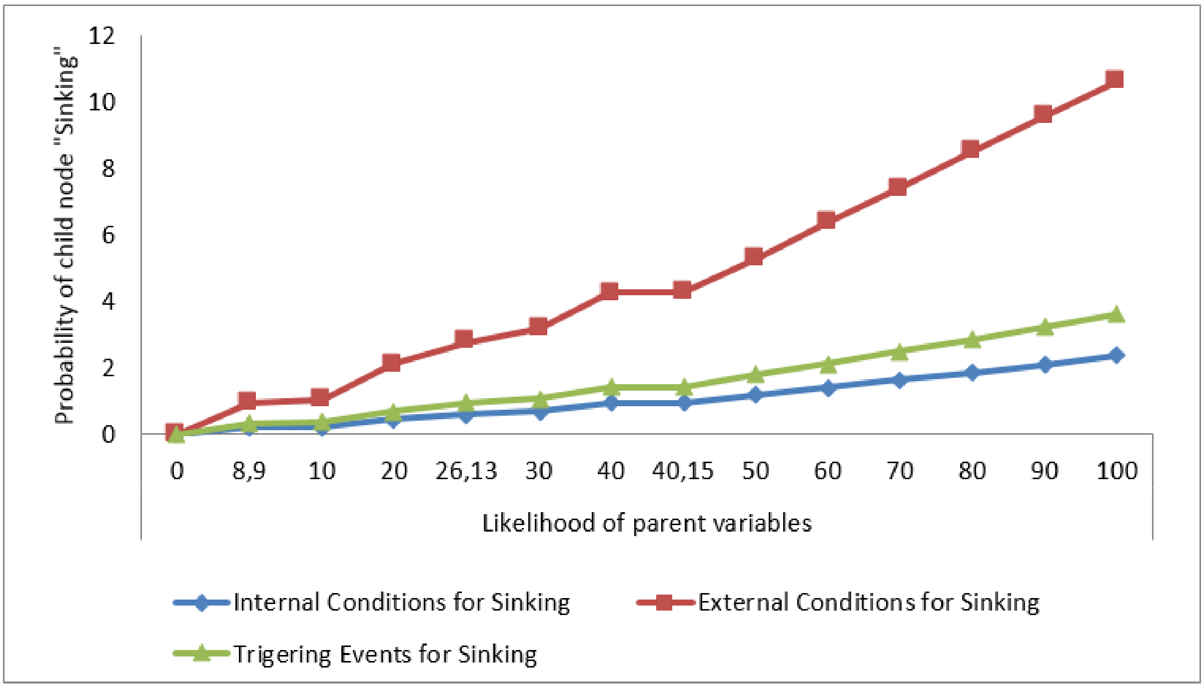

Figure 11. Change of probabilities for the node ‘Sinking’

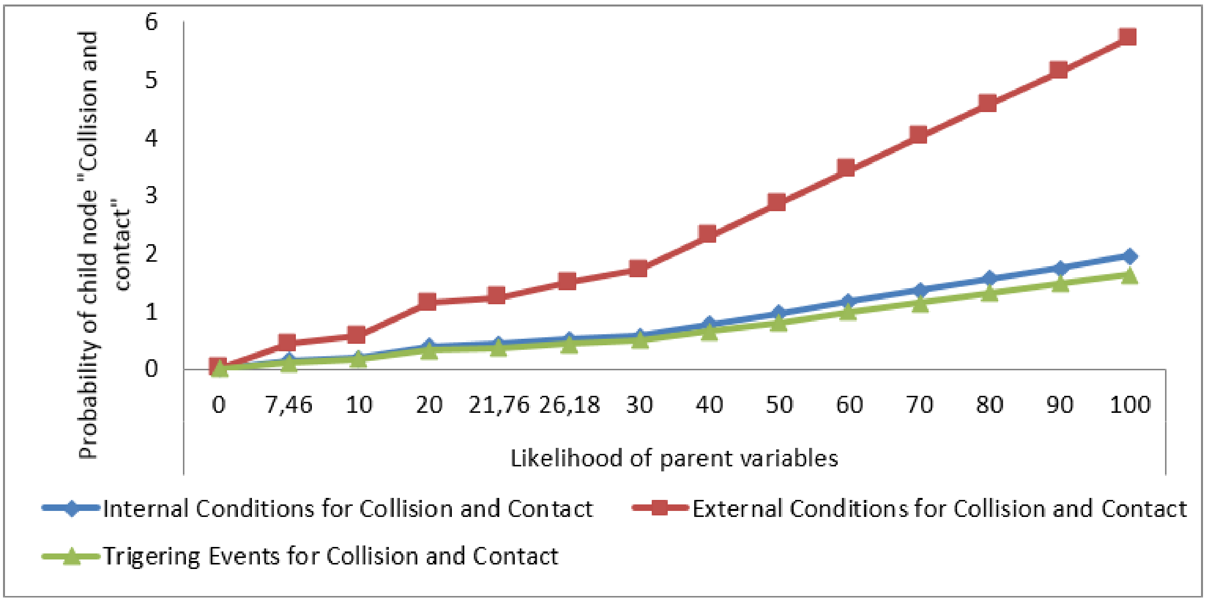

Figure 12. Change of probabilities for the node ‘Collision and Contact’

6.3. Axiom 3

Axiom 3 requires that sub-evidence should have less influence on the values of a child node than evidence received from the parent nodes, ‘Triggering event for grounding’ (evidence) is composed of ‘Navigation on Storm’, ‘Use of Vessel within Limits of Design Conditions’ and ‘Manoeuvre of BTM’ (all sub-evidence). When evidence is entered (100%) into the nodes and states of ‘Navigation on Storm=Yes’, ‘Use of Vessel within Limits of Design Conditions=Yes’ and ‘Manoeuvre of BTM=Inappropriate’, the posterior probabilities of ‘Grounding=Yes’ are 2.29%, 2.50% and 2.08% respectively. When ‘Use of Vessel within Limits of Design Conditions=Yes’, ‘Navigation on Storm=Yes’ and ‘Manoeuvre of BTM=Inappropriate’ are entered into the model, the probability of ‘Grounding=Yes’ increases to 3.02%. Thus, the BN model can be said to satisfy Axiom 3. Further tests were also conducted for all accident nodes together with their corresponding sub-evidence. All the obtained results are in harmony with Axiom 3.

6.4. Sensitivity Analysis and Application of the BN Model

Entropy reduction was used to determine the nodes to be subjected to a sensitivity analysis. Hugin software was used for entropy reduction and sensitivity analysis in this study (Hugin, 2018). Entropy reduction allows for the identification of the most important nodes affecting accident occurrence for each HFCAS level. Table 12 shows entropy reduction results for each accident category. Nodes that are independent from the accident nodes in the table are not included.

Table 12. Entropy reduction results for each accident category

HFACS Level	Node (%100)	Entropy reduction for sinking (%100)	Entropy reduction for grounding (%100)	Entropy reduction for collision-contact (100%)
Internal conditions	Inland vessel	1.67	1.85	-
	Vessel age	5.65	2.85	-
	Malfunction	8.28	-	2.74
External conditions	Navigation area/NW	-	-	-
	Navigation area/PORT	-	-	12.57
	Navigation area/CW	16.52	-	1.38
	Navigation area/OS	-	-	-
	Navigation area/ANC	0.35	27.05	1.62
	Visibility	-	-	42.87
	Heavy weather and sea conditions	12.96	9.74	-
Unsafe acts	Navigation on storm	32.4	61.91	36.8
	Use of vessel within limits of design conditions	17.6	30.99	-
	Cargo shifting or inappropriate stability	14.68	-	-
	Departure from port HWSC	5.64	8.96	7.9
	Anchorage area selection	7.52	14.24	10.08
	Manoeuvre of watch officer	-	-	23.4
	Manoeuvre of pilot	-	17.85	11.59
	Manoeuvre of captain	-	40.84	52.28
	Manoeuvre of BTM	-	50.72	68.56
	COLREG	-	-	57.35
	Tug boat operation	-	8.26	11.73
Pre-condition for unsafe act	Vessel navigation operation management	29.59	53.83	53.55
	Port operation management	11.84	15.95	19.92
	Pilot operation management	-	6.91	10.36
	Fatigue	0.35	0.85	1.08
	Situational awareness	2733	44.49	57.44
	External internal communication	27.14	45.51	55.34
	Vessel cargo operation management	9.62	-	-
Unsafe supervision	Planned maintenance	3.3	1.62	-
	Vessel navigation operation planning	26.17	46.39	47.42
	Vessel cargo operation planning	9.91	-	-
	Port operation planning	11.84	15.95	19.91
	Inadequate manning	1.55	3.64	4.86
	Observation during operation	27.24	45.06	56.26
Organizational influence	Training and familiarization	14.05	25.27	25.5
	Oversight and control	25.84	39.63	49.38
	Port or company pressure	3.4	5.92	6.22
	Company manning strategy	1.55	3.64	4.86
	Procedure	3.92	5.87	7.34
	Crew assignment	12.14	19.66	22.75

Considering the entropy reduction results shown in Table 12, for each HFACS level, sensitivity analysis was applied to the three nodes that demonstrated the greatest effect on each individual accident node. While the other nodes remain constant, the changes in the probability of each accident category was examined inserting evidence into the parent nodes, which are subjected to sensitivity analysis, first at 0% and then at 100%. The results of the sensitivity analysis results for sinking, grounding and collision-contact consequence nodes are demonstrated in Figures 13, 14 and 15. At this stage of the study, the aim is to demonstrate the effects that the outlined nodes, in each level of the BN, have on the occurrence of accidents.

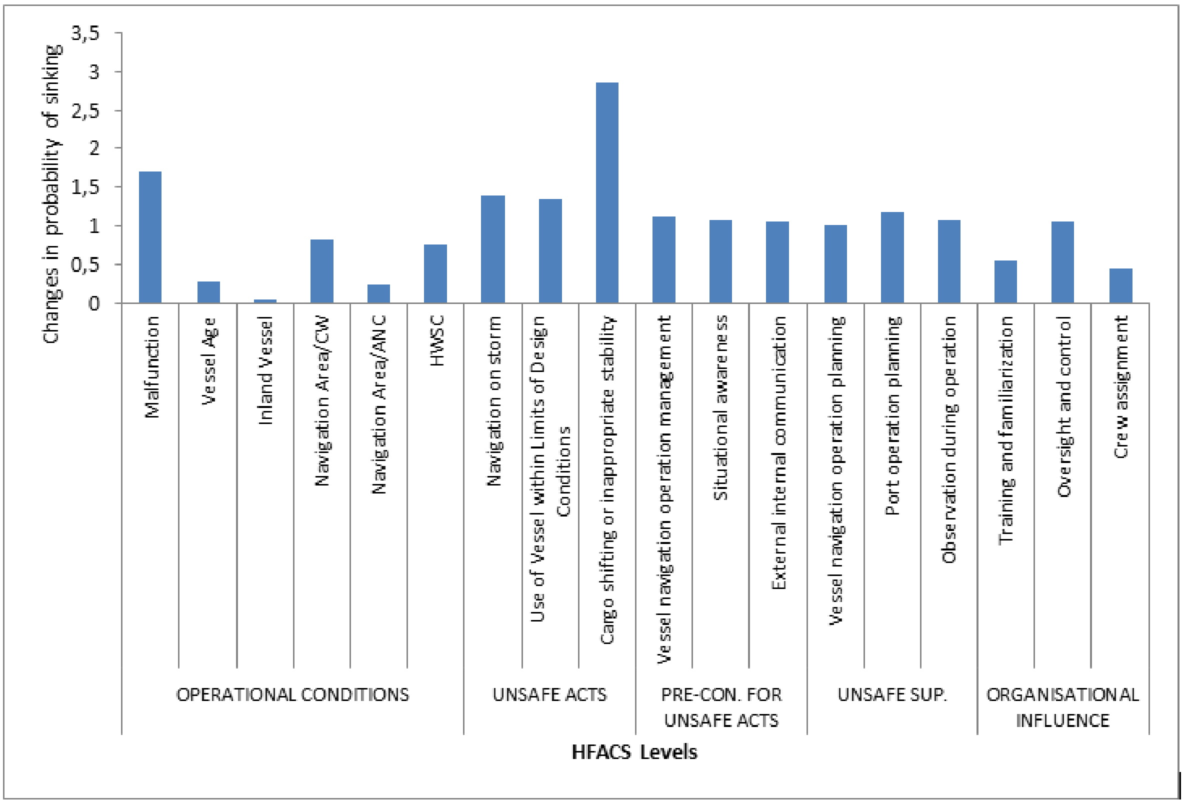

Figure 13. Sensitivity analysis results for sinking

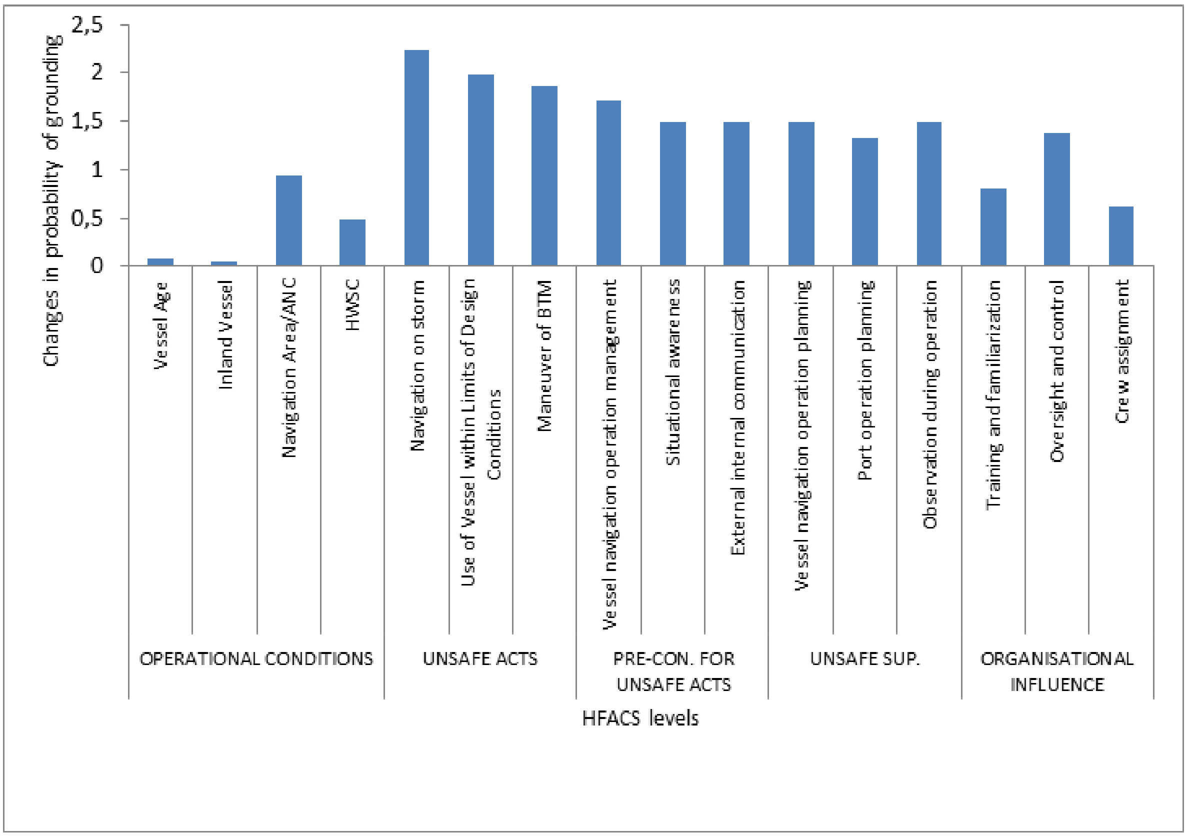

Figure 14. Sensitivity analysis results for grounding

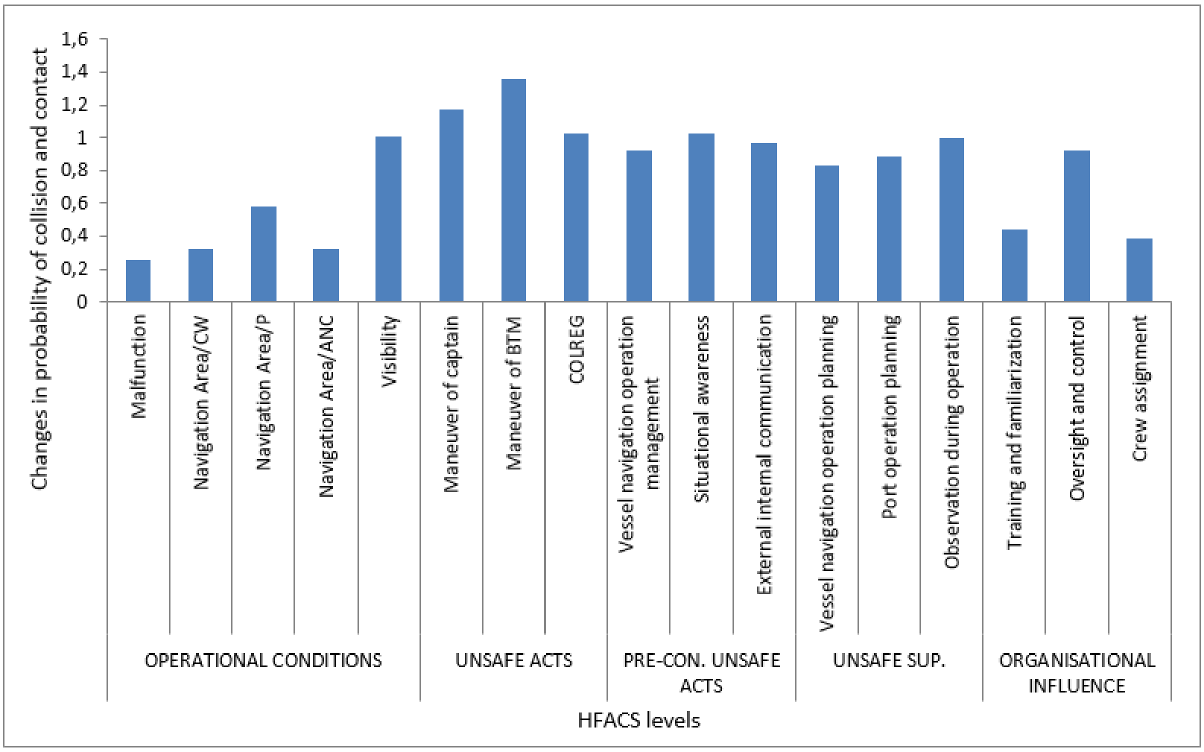

Figure 15. Sensitivity analysis results for collision-contact

In the second stage of the sensitivity analysis, with a similar approach mentioned above, considering the occurrence of accidents in the Black Sea, sensitivity analysis has been applied to internal conditions, external conditions and triggering event nodes, which are the final stages of accident formation. The purpose of this step is to identify the three nodes that have the greatest effect on the accident nodes. The results of the sensitivity analysis are presented in Figure 16.

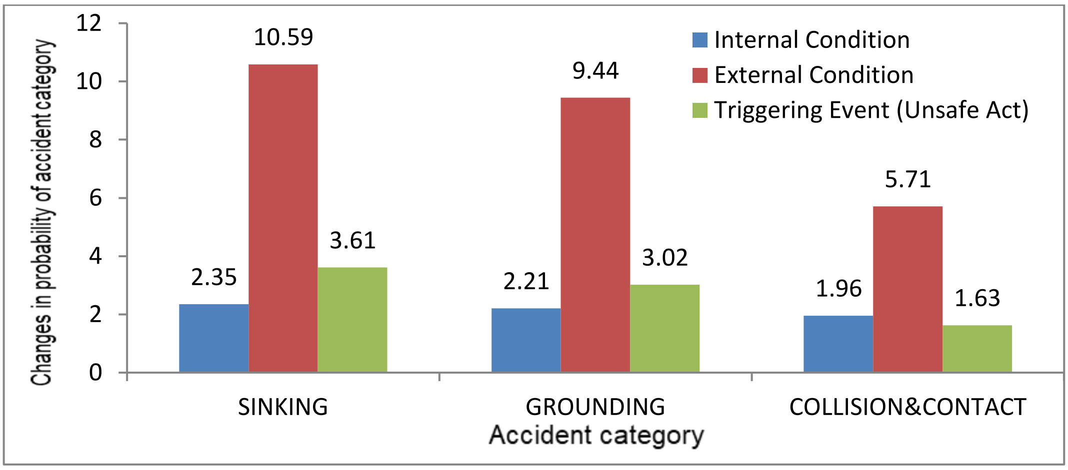

Figure 16. Sensitivity analysis results of main nodes

The final step in the sensitivity analysis is to determine the accident combinations and the occurrence probability of an accident. In order to determine this, the probabilities of the nodes demonstrating the greatest effect under ‘triggering events’, ‘external conditions’ and ‘internal conditions’ were evaluated. This evaluation involves inserting 100% evidence into the probability values of the relevant parent nodes. The purpose of this is to observe the changes in the posterior probability of the consequence nodes. According to the results of the analysis, 51 accident combinations were determined for the accident consequence nodes, 27 accident combinations for sinking accidents, 12 for grounding and 12 for collision-contact. The accident combinations consist of the following: internal_condition + external_condition + triggering_event. Table 13 shows the 10 most likely accident combinations with the highest probabilities and their percentage values.

Table 13. Most likely accident combinations for each accident category

No	10 most likely combinations of accident formation								
	Sinking (initial probability: 0.94%)			Grounding (initial probability: 0.79%)			Collision and contact (initial probability: 0.43%)		
	Combinations	Posterior probability (comb. %100)	Rate of change	Combinations	Posterior probability (comb. %100)	Rate of change	Combinations	Posterior probability (comb. %100)	Rate of change
1.	CSOIS-MAL-CW	13.23	13.1	UVLDC-VA-ANC	5.18	5.6	MOBTM-MAL-VIS	4.69	9.9
2.	CSOIS-MAL-HWSC	9.37	9.0	UVLDC-IV-ANC	5	5.3	MOC-MAL-VIS	4.55	9.6
3.	CSOIS-MAL-ANC	8.17	7.7	NOS-IV-ANC	4.85	5.1	COREG-MAL-VIS	3.42	7.0
4.	UVLDC-MAL-CW	7.81	7.3	NOS-VA-ANC	4.77	5.0	MOBTM-MAL-P	2.76	5.4
5.	NOS-MAL-CW	7.02	6.5	MOBTM-IV-ANC	4.42	4.6	MOC-MAL-P	2.68	5.2
6.	CSOIS-VA-CW	6.5	5.9	MOBTM-VA-ANC	4.32	4.5	COLREG-MAL-P	2.01	3.7
7.	CSOIS-IV-CW	6.01	5.4	UVLDC-VA-HWSC	2.91	2.7	MOBTM-MAL-ANC	1.76	3.1
8.	UVLDC-MAL-HWSC	5.53	4.9	UVLDC-IV-HWSC	2.8	2.5	MOBTM-MAL-CW	1.75	3.1
9	NOS-MAL-HWSC	4.98	4.3	NOS-IV-HWSC	2.72	2.4	MOC-MAL-ANC	1.71	3.0
10	CSOIS-VA-HWSC	4.61	3.9	NOS-VA-HWSC	2.67	2.4	MOC-MAL-CW	1.7	3.0

6.5. Sinking Accidents

Sinking accidents are the most common accident type that occur on the Black Sea and demonstrate the most serious consequences in terms of economic loss, loss of life and environmental pollution. The results show that external operational conditions play an important role in the occurrence of all three-accident categories; however, they have the greatest effect on sinking accidents as shown in Figure 16. The nodes that demonstrate the greatest effects in the occurrence of sinking accidents, under external conditions, are: ‘navigation in coastal waters’ (0.83%) and ‘heavy weather and sea conditions’ (0.76%). The internal conditions demonstrating the greatest effect on sinking are: ‘malfunctions’ (1.7%), ‘old vessel structure’ (0.28%) and ‘river type vessel structure’ (0.05%) as shown in Figure 13.

Unsafe actions are events that trigger accidents, and according to the results of the study they are the second most important factors in the occurrence of sinking accidents. The most important unsafe acts playing a role in the occurrence of sinking accidents: ‘cargo shifting or inappropriate stability’ (2.87%), ‘navigation on storm’ (1.39%), and ‘Use of Vessel within Limits of Design Conditions’ (1.34%) (Figure 13).

Organizational influences and improper internal-external management activities (latent failures) form the basis for the potential occurrence of unsafe actions. According to the results of the study, the determined latent failures that lead to unsafe acts are: ‘navigation operation management’ (1.12%) (Pre-condition for unsafe act), ‘port operation planning’ (1.17%) (Unsafe supervision) and ‘oversight and control’ (1.06%) (Organizational influence) (Figure 13).

Marine accident occurrences have a compact structure, and according to the BN model, favourable operational conditions are necessary along with unsafe actions in order for an accident to occur. Evaluating the causes of accidents separately, as well as in certain combinations, makes it possible to understand accident occurrence. According to the BN results, the most likely scenarios which cause sinking accidents in the Black Sea involve combinations of: Cargo Shifting Or Inappropriate Stability (CSOIS), Malfunction (MAL) and ‘Coastal Waters’ (CW)/‘Heavy Weather and Sea Conditions’ (HWSC)/ ‘Anchorage’ (ANC). The probability of sinking given the specified combinations increases by a minimum of 8 times and a maximum of 14 times, which can be seen in Table 13. For these combinations, bad weather conditions and navigation area are complementary elements to the accident. When examining other event combinations in the occurrence sinking accidents, it was observed that ‘inland vessel structure’ and ‘old hull structure’ also affected the occurrence of sinking accidents. This is also demonstrated in Table 13.

6.6. Grounding Accidents

Grounding accidents are the second most frequent category of marine accidents in the Black Sea. According to the BN results, external conditions (9.44%) have the greatest effect on the occurrence of grounding accidents, followed by unsafe acts (3.02%) and internal conditions (2.21%), as shown in Figure 16. The nodes that demonstrated the greatest effects on the occurrence of grounding accidents, under external conditions, are: ‘navigation area/anchorage’ (0.94%) and ‘heavy weather and sea conditions’ (0.48%). Furthermore, when a ship is in an anchorage area and is exposed to bad weather conditions, it is more likely to run aground. Following the examination of the internal conditions, it was observed that the ‘use of old vessels’ (0.08%) and ‘use of river type vessels’ (0.05%) in the Black Sea increase the likelihood of a grounding accident. This is demonstrated in Figure 14.

As with sinking accidents, unsafe actions are the second most important level in the occurrence of grounding accidents following external conditions. The unsafe actions that demonstrate the greatest effect on the occurrence of grounding accidents in the Black Sea are: ‘navigation on storm’ (2.23%), and ‘the use of vessel within limits of design conditions’ (1.99%) respectively. The use of old vessels or river type vessels in bad weather conditions or in condition of exceeding a vessel`s design limits increase the likelihood of grounding accidents (Figure 14).

The nodes that demonstrate the greatest effects in the formation of unsafe actions, under latent factors are: ‘vessel navigation operation management’ (1.72%) (Pre-condition for unsafe act), ‘observation during operation’ (1.5%) (Unsafe supervision) and ‘oversight and control’ (1.37%) (Organizational influence) (Figure 14).

According to the results of the study, the most likely scenarios for grounding are the combinations of ‘Use of Vessel within Limits of Design Conditions’ (UVLDC), ‘Anchorage’ (ANC) and ‘Old Vessel’ (OV)/’Inland Vessel’ (IV). The probability of grounding in the stated combinations increases by approximately 6 times. Old vessel structures or river type vessel structures are important factors in this combination as complementary factors (Table 13). Similarly, as with the previously mentioned accident combinations (UVLDC + ANC + (OV or IV)), there are old vessel structures or river type vessel structures in other accident combinations.

6.7. Collision-Contact Accidents

Collision-Contact is the third most common accident category in the Black Sea. It has been observed that the effect of external conditions (5.71%) on the occurrence of collision-contact accidents is lower than the effects of external conditions demonstrated with the other accident types. However, it is the most important level that plays a role in the occurrence of collision-contacts (Figure 16). Visibility (1.01%) is the most important external condition that affects the occurrence of collision-contact accidents. Other important external conditions affecting collision-contact accidents are: ‘navigating in port area’ (0.58%), ‘anchorage area’ (0.32%) and ‘coastal waters’ (0.32%). Navigation area and restricted visibility establish a base for the occurrence of collision-contact accidents. Furthermore, it was observed that old vessel structures or river type vessels, under the level of the internal conditions, do not affect the occurrence of collision-contact accidents. However, malfunctions that occur within a ship’s components affect collision-contact accident occurrence (0.26%), as demonstrated in Figure 15.

The results of the study show that the actions of bridge team members have a greater effect on collision-contact accidents than other accident types. The most influential unsafe acts are: ‘inappropriate manoeuvre of BTM’ (1.36%), ‘inappropriate manoeuvre of captain’ (1.17%) and ‘violation of COLREG’ (1.03%). When the latent failures are examined, unlike grounding and sinking accidents, the most effective pre-condition for collision–contact accidents is ‘loss of situational awareness’ (1.03%). According to the results of the BN analysis, loss of situational awareness of bridge team members leads to unsafe acts (error and violations). Similarly, as observed with sinking and grounding accidents, ‘unclear observation during operation’ (1.0%) (Unsafe supervision) and ‘inadequate oversight and control’ (0.92%) (Organizational influence) are the most effective latent failures in collision-contact accidents (Figure 15).

The most likely accident scenarios for collision-contact accidents are combinations of: ‘Malfunction’ (MAL) and ‘Visibility’ (VIS) nodes along with ‘Manoeuvre of Bridge Team Members’ (MOBTM) or ‘Manoeuvre of Captain’ (MOC) or COLREG nodes (MAL + VIS + (MOBTM or MOC or COLREG)). In these combinations, the likelihood of collision-contact increases by a minimum of 8 times and a maximum of 10 times as shown by Table 13. This result shows that a mistake made by bridge team members may lead to an accident when there is a malfunction on the ship, as in the case of restricted visibility, such as during the night or in heavy fog. In addition, other important combinations that increase the likelihood of an accident are the MOBTM or MOC or COLREG nodes in conjunction with port, anchorage or coastal waters.

7. DISCUSSION

This is the first study that analyses the accidents that have occurred in the entire Black Sea area as a collective. Many studies in the scope of marine accident analysis emphasize that the most frequent accident categories at sea are collision-contact accidents and grounding accidents, respectively (Uğurlu et al., 2015b; Uğurlu et al., 2015c). However, unlike other studies in the literature, this study has determined that the most frequent accident categories in the Black Sea are sinking, grounding and collision-contact accidents, respectively. In addition, an accident network which summarizes the accident occurrence in the Black Sea has been established by using the Bayesian network method. Using this accident network, the combination of accident occurrences in the Black Sea for all three accident categories has been revealed and interpreted.

Operational conditions play an important role for all three accident categories in the areas of the Black Sea where accidents are heavily concentrated. The results of the study show that the operational conditions have the greatest effect on the occurrence of sinking and grounding accidents. The most common operational conditions that contribute to the occurrence of both grounding and sinking accidents, were determined to be ‘navigation area’ (coastal water and anchorage) and ‘heavy weather and sea conditions’. Many studies carried out in the context of accident analysis have emphasized that ‘heavy weather and sea conditions’ are the main factor in the occurrence of grounding or sinking accidents (Macrae, 2009; Ulusçu et al., 2009; Schröder-Hinrichs et al., 2011; Mullai and Paulsson, 2011; Uğurlu et al., 2015b; Uğurlu et al., 2015a).

One important feature that distinguishes this study from other studies in the literature is that, malfunctions and old or inland (river type) vessel structures are found to be factors which also greatly affect the occurrence of accidents, heavy weather conditions. When navigating with old vessels or inland vessels in the Black Sea, inappropriate anchorage area selection or navigating in heavy weather conditions, by ignoring the weather reports, or use of vessel within limits of design conditions, or inappropriate cargo stowage, will inevitably result in grounding and sinking accidents.

In addition to the operational conditions and unsafe acts that play a role in the occurrence of grounding, and sinking accidents, latent failures were also identified in the study, within the scope of marine accident analysis. For this reason, in order to prevent accidents in the Black Sea, it is necessary to focus on factors under pre-conditions, unsafe supervision and organizational influences, such as ‘inappropriate crew assignment’, ‘inadequate manning’, ‘inappropriate planned operations’, and ‘lack of communication and coordination’.

As a result of this study, accidents were observed to be in high concentrations in the coastal waters of the Black Sea, especially in Kerch Strait North and South Bound (Ukraine), Novorossiysk (Russia), Kilyos (Istanbul-Turkey), Constanta (Romania), Riva (Istanbul - Turkey) and Batumi (Georgia). The Black Sea is a maritime area where many ships navigate, and many vessels that operate in the area share common features such as very old vessels, or vessels intended for use on inland waterways (*i.e.* rivers). The average age of the vessels involved in grounding or sinking accidents was 28.2 years and the average age of the inland vessels was 30.3 years. Therefore, in order to reduce accidents in the Black Sea, the factors under 'internal conditions' ('old vessel structure', 'inland vessel structure' and 'malfunctions') must almost certainly be improved. In order to reduce grounding and sinking accidents in the Black Sea, it is necessary to prevent navigation of river type vessels which are not suitable for heavy weather and sea conditions due to their structure, and vessels with older structures must be renewed or replaced.

The results of the analysis related to collision-contact accidents are similar to the results found in literature (Chauvin et. al., 2013; Uğurlu et. al., 2015c; Uğurlu et al., 2018). Unsafe acts that play a role in the occurrence of collision-contact accidents were determined as: 'inappropriate manoeuvre of captain' or 'BTM', and 'violation of COLREG'. The latent failures underlying these unsafe acts are: 'loss of situational awareness', 'lack of external and internal communication', 'inappropriate navigation operation management', 'unclear observation during operation', and 'inappropriate oversight and control'. In this study, it was observed that unsafe actions are more likely to occur under the external conditions category, under such factors as, 'restricted visibility', 'heavy weather' and 'restricted waterways' (port, anchorage or coastal water). It is not possible to eliminate factors under external conditions, but these risks can be kept under control by assigning experienced team members who have worked in the area for a sufficient period of time.

8. CONCLUSION

The most important feature of this study is an accident network which summarizes the occurrence of accidents in the Black Sea. The accident network enables users to estimate the risk of accidents in variable conditions. The purpose of this is to increase the situational awareness of users and prevent accidents with the established Bayesian Network. Also in this study, risk factors affecting accident occurrence in Black Sea were determined and recommendations were presented to assist with the mitigation of these factors. In this way, ship operators, port/flag state authorities or company owners can estimate the risk of accidents by taking into account the changing conditions and may intervene in terms of the ships' navigation. The model presented in this study was formulated and validated by the analysis of accidents in the Black Sea. Since the foundation of the network is based on HFACS, it has a highly adaptable and updateable structure. Therefore, it is completely reasonable to suggest that the application of the methodology can be extended to analyses accidents occurring in different marine areas.

HFACS has been used as modified for adaptation to a number of industries such as, aviation (Wiegmann and Shappell, 2001; Shappell and Wiegmann, 2004; Dambier and Hinkelbein, 2006), maritime (Chen et. al., 2013; Uğurlu et. al., 2018), railway (Baysari et. al., 2008), mining (Patterson and Shappell, 2010; Lenné et. al., 2012), and the oil and gas industry (Theophilus ., 2017). Therefore, the network structure presented in this study can be modified and used for risk analysis in cases of uncertainty both in maritime transport and other sectors.

The data collection method utilised, in to develop the BN, proved to be challenging due to the lack of a coherent accident database relating to accidents in the Black Sea. Furthermore, the analysed accident reports were read in four different languages (Turkish, Russian, Georgian, and Ukrainian) since the accidents are not reported and documented in English. For this reason, it is necessary to establish a common EMSA-like accident database, which collects, compiles and standardizes accident reports, as well as integrating maritime safety regulations in countries that have coasts on the Black Sea. This will allow documented accident reports to be standardized. This would open the possibility of accidents to be reported directly to the International Maritime Organization (IMO), via the database, and assisting future researchers by easing the burden of gathering accident statistics in the Black Sea region.

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APPENDIX

Table A1. Probabilities of nodes under organizational influences

Crew Assignment

Qualified Crew	0.506
Unqualified Crew	0.494

Procedure	
Appropriate	0.944
Inappropriate	0.056

Company’s Manning Strategy	
Optimum Safe Manning	0.899
Minimum Safe Manning	0.101

Port or company pressure	
Yes	0.067
No	0.933

		Crew Assignment	
		Qualified Crew	Unqualified Crew
Training and Familiarization	Sufficient	0.644	0.227
	Insufficient	0.356	0.773

	Training and Familiarization	Insufficient								Sufficient							
	Procedure	Inappropriate				Appropriate				Inappropriate				Appropriate			
	Port or Company Pressure	Yes		No		Yes		No		Yes		No		Yes		No	
	Crew Assignment	Qualified	Unqualified	Qualified	Unqualified	Qualified	Unqualified	Qualified	Unqualified	Qualified	Unqualified	Qualified	Unqualified	Qualified	Unqualified	Qualified	Unqualified
Oversight and Control	Adequate	0	0	0	0	0.5	0	0.75	0.437	0	0	0	0	0.667	0	1	0.75
	Inadequate	1	1	1	1	0.5	1	0.25	0.563	1	1	1	1	0.333	1	0	0.25

Table A2. Probabilities of nodes under unsafe supervision

	Oversight and Control	Adequate	Inadequate
Planned Maintenance	Completed	1	0.959
	Uncompleted	0	0.041

	Port or Company Pressure	Yes				No			
	Oversight and Control	Adequate		Inadequate		Adequate		Inadequate	
	Training and Familiarization	Insufficient	Sufficient	Insufficient	Sufficient	Insufficient	Sufficient	Insufficient	Sufficient
Vessel Navigation Operation Planning	Unsafe	0.7	0.5	1	1	0.333	0	1	0.485
	Safe	0.3	0.5	0	0	0.667	1	0	0.515

	Oversight and Control	Adequate	Inadequate
Vessel Cargo Operation Planning	Adequate	1	0.89
	Inadequate	0	0.11

	Oversight and Control	Adequate	Inadequate
Port Operation Planning	Adequate	1	0.699
	Inadequate	0	0.301

	Company Manning Strategy	Minimum Safe Manning	Optimum Safe Manning
Inadequate Manning	No	0	1
	Yes	1	0

	Oversight and Control	Adequate				Inadequate			
	Vessel Navigation Operation Planning	Unsafe		Safe		Unsafe		Safe	
	Inadequate Manning	Yes	No	Yes	No	Yes	No	Yes	No
Observation During Operation	Clear	0.333	0.687	0.667	1	0	0	0	0.32
	Unclear	0.667	0.313	0.333	0	1	1	1	0.68

Table A3. Probabilities of nodes under pre-conditions for unsafe acts

	Inadequate Manning	Yes	No
Fatigue	Yes	0.111	0
	No	0.889	1

	Port Operation Planning	Adequate								Inadequate							
	Vessel Cargo Operation Planning	Adequate				Inadequate				Adequate				Inadequate			
	Observation During Operation	Clear		Unclear		Clear		Unclear		Clear		Unclear		Clear		Unclear	
	Fatigue	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Situational Awareness	Sufficient	0.25	1	0	0.05	0.15	0.333	0	0	0.2	0.615	0	0	0	0	0	0
	Insufficient	0.75	0	1	0.95	0.85	0.667	1	1	0.8	0.385	1	1	1	1	1	1

	Observation During Operation	Clear		Unclear	
	Situational Awareness	Sufficient	Insufficient	Sufficient	Insufficient
External Internal Communication	Adequate	0.956	0.5	0.75	0
	Inadequate	0.044	0.5	0.25	1

	Situational Awareness	Sufficient		Insufficient	
	Vessel Cargo Operation Planning	Adequate	Inadequate	Adequate	Inadequate
Vessel Cargo Operation Management	Safe	1	0.167	1	0.143
	Unsafe	0	0.833	0	0.857

	Port Operation Planning	Adequate				Inadequate			
	External Internal Communication	Adequate		Inadequate		Adequate		Inadequate	
	Situational Awareness	Sufficient	Insufficient	Sufficient	Insufficient	Sufficient	Insufficient	Sufficient	Insufficient

	Vessel Navigation Operation Planning	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe
Vessel Navigation Operation Management	Safe	0.26	1	0	0.54	0	0.5	0	0.04	0	0.7	0.25	0.24	0	0.2	0	0
	Unsafe	0.74	0	1	0.46	1	0.5	1	0.96	1	0.3	0.75	0.76	1	0.8	1	1

	Port Operation Planning	Adequate		Inadequate	
	Situational Awareness	Sufficient	Insufficient	Sufficient	Insufficient
Port Operation Management	Safe	1	1	0.125	0
	Unsafe	0	0	0.875	1

	Port Operation Planning	Adequate		Inadequate	
	External Internal Communication	Adequate	Inadequate	Adequate	Inadequate
Pilot Operation Management	Safe	1	1	0.857	0.65
	Unsafe	0	0	0.143	0.35

Table A4. Probabilities of nodes under unsafe acts

	External Internal Communication	Adequate				Inadequate			
	Situational Awareness	Sufficient		Insufficient		Sufficient		Insufficient	
	Vessel Navigation Operation Management	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe
COLREG	Not Violated	1	1	1	1	1	1	1	0
	Violated	0	0	0	0	0	0	0	1

	Pilot Operation Management	Safe		Unsafe	
	Port Operation Management	Safe	Unsafe	Safe	Unsafe
Tugboat Operation	Operational	1	0.846	0.25	0
	Faulty	0	0.154	0.75	1

	Tugboat Operation	Operational				Faulty			
	Pilot Operation Management	Safe		Unsafe		Safe		Unsafe	
	Port Operation Management	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe
Manoeuvre of Pilot	Appropriate	1	0.924	0	0	1	1	0	0
	Inappropriate	0	0.076	1	1	0	0	1	1

	Situational Awareness	Sufficient		Insufficient	
	Vessel Navigation Operation Management	Safe	Unsafe	Safe	Unsafe
Manoeuvre of Captain	Appropriate	1	0.18	0	0.5
	Inappropriate	0	0.82	1	0.5

	Port Operation Management	Safe		Unsafe	
	Vessel Navigation Operation Management	Safe	Unsafe	Safe	Unsafe
Departure from Port in Heavy Weather and Sea Condition	No	1	0.986	0.833	0.625
	Yes	0	0.014	0.167	0.375

	Vessel Navigation Operation Management	Safe	Unsafe

Anchorage Area Selection	Appropriate	1	0.805
	Inappropriate	0	0.195

	Situational Awareness	Sufficient		Insufficient	
	Vessel Navigation Operation Management	Safe	Unsafe	Safe	Unsafe
Manoeuvre of Watch keeping Officer	Appropriate	1	1	1	0.786
	Inappropriate	0	0	0	0.214

	Manoeuvre of Pilot	Appropriate				Inappropriate			
	Manoeuvre of Captain	Appropriate		Inappropriate		Appropriate		Inappropriate	
	Manoeuvre of Watch keeping Officer	Appropriate	Inappropriate	Appropriate	Inappropriate	Appropriate	Inappropriate	Appropriate	Inappropriate
Manoeuvre of Bridge Team Members (BTM)	Appropriate	1	0	0	0	0	0	0	0
	Inappropriate	0	1	1	1	1	1	1	1

	Departure from Port in Heavy Weather and Sea Condition	No				Yes			
	Anchorage Area Selection	Appropriate		Inappropriate		Appropriate		Inappropriate	
	Vessel Navigation Operation Management	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe	Safe	Unsafe
Navigation on Storm	No	1	0.364	0.667	0.133	0.667	0	0.333	0
	Yes	0	0.636	0.333	0.867	0.333	1	0.667	1

	Inland Vessel	Yes		No	
	Navigation on Storm	No	Yes	No	Yes
Use of Vessel in Condition of Exceeding Design Limit	No	1	0.2	1	0.75
	Yes	0	0.8	0	0.25

	Port Operation Management	Safe		Unsafe	
	Vessel Cargo Operation Management	Safe	Unsafe	Safe	Unsafe
Cargo Shifting or Inappropriate Stability	No	1	0	0.818	0
	Yes	0	1	0.182	1

	Cargo Shifting or Inappropriate Stability	No				Yes			
	Use of Vessel in Condition of Exceeding Design Limit	No		Yes		No		Yes	
	Navigation on Storm	No	Yes	No	Yes	No	Yes	No	Yes
Triggering Event for Sinking	Observed	0.12	0.4	0.333	0.52	1	1	0.667	1
	Unobserved	0.88	0.6	0.667	0.48	0	0	0.333	0

	Manoeuvre of BTM	Appropriate				Inappropriate			
	Use of Vessel in Condition of Exceeding Design Limit	No		Yes		No		Yes	
	Navigation on Storm	No	Yes	No	Yes	No	Yes	No	Yes
Triggering Event for Grounding	Observed	0	0.44	0.333	0.458	0.154	0.833	0.667	1
	Unobserved	1	0.56	0.667	0.542	0.846	0.167	0.333	0

	Navigation on Storm	No				Yes			
	COLREG	Not Violated		Violated		Not Violated		Violated	
	Manoeuvre of BTM	Appropriate	Inappropriate	Appropriate	Inappropriate	Appropriate	Inappropriate	Appropriate	Inappropriate
Triggering Event for Collision and Contact	Observed	0	0.467	0	1	0.041	0	0	1
	Unobserved	1	0.533	1	0	0.959	1	1	0

Table A5. Probabilities of nodes under operational conditions

Vessel Age	%
Old	0.753
New	0.247

	Planned Maintenance	Completed		Uncompleted	
	Vessel Age	Old	New	Old	New
Malfunction	Observed	0.047	0	1	0.667
	Unobserved	0.953	1	0	0.333

Inland Vessel	%
Yes	0.348
No	0.652

	Vessel Cargo Operation Management	Safe	Unsafe
Internal Operational Conditions for Collision and Contact	Observed	0.25	0.216
	Unobserved	0.75	0.784

	Vessel Age	Old	New
Internal Operational Conditions for Grounding	Observed	0.373	0.318
	Unobserved	0.627	0.682

	Malfunction	Observed		Unobserved	
	Vessel Age	Old	New	Old	New
Internal Operational Conditions for Sinking	Observed	1	0	0.393	0.318
	Unobserved	0	1	0.607	0.682

Navigation Area	%
Narrow Water	0.146
Port	0.191
Coastal Water	0.258
Open Sea	0.135
Anchorage	0.27

Visibility	%
Poor	0.236
Good	0.764

HWSC	%
Yes	0.798
No	0.202

	Visibility	Poor	Good

	Navigation Area	Narrow Water	Port	Coastal Water	Open Sea	Anchorage	Narrow Water	Port	Coastal Water	Open Sea	Anchorage
External Operational Conditions for Collision and Contact	Observed	0.048	0.142	0.333	0.095	0.286	0.015	0.118	0	0.029	0.015
	Unobserved	0.952	0.858	0.667	0.905	0.714	0.985	0.882	1	0.971	0.985

	Heavy Weather and Sea Conditions	Yes					No				
	Navigation Area	Narrow Water	Port	Coastal Water	Open Sea	Anchorage	Narrow Water	Port	Coastal Water	Open Sea	Anchorage
External Operational Conditions for Grounding	Observed	0.086	0.014	0.086	0	0.211	0	0.228	0	0	0
	Unobserved	0.914	0.986	0.914	1	0.789	1	0.772	1	1	1

	Heavy Weather and Sea Conditions	Yes					No				
	Navigation Area	Narrow Water	Port	Coastal Water	Open Sea	Anchorage	Narrow Water	Port	Coastal Water	Open Sea	Anchorage
External Operational Conditions for Sinking	Observed	0.085	0	0.183	0.099	0.113	0	0.167	0	0	0
	Unobserved	0.915	1	0.817	0.901	0.887	1	0.833	1	1	1

Table A6. Probabilities of accidents

	Internal Operational Conditions for Sinking	Observed				Unobserved			
	External Operational Conditions for Sinking	Observed		Unobserved		Observed		Unobserved	
	Triggering Event for Sinking	Observed	Unobserved	Observed	Unobserved	Observed	Unobserved	Observed	Unobserved
Sinking	Yes	1	0	0	0	0	0	0	0
	No	0	1	1	1	1	1	1	1

	External Operational Conditions for Grounding	Observed		Unobserved	
	Internal Operational Conditions for Grounding	Observed	Unobserved	Observed	Unobserved

	Triggering Event for Grounding	Observed	Unobserved	Observed	Unobserved	Observed	Unobserved	Observed	Unobserved
Grounding	Yes	1	0	0	0	0	0	0	0
	No	0	1	1	1	1	1	1	1

	External Operational Conditions for Collision and Contact	Observed				Unobserved			
	Internal Operational Conditions for Collision and Contact	Observed		Unobserved		Observed		Unobserved	
	Triggering Event for Collision and Contact	Observed	Unobserved	Observed	Unobserved	Observed	Unobserved	Observed	Unobserved
Collision and Contact	Yes	1	0	0	0	0	0	0	0
	No	0	1	1	1	1	1	1	1

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