IAMU 2021 Research Project
(No. YAS202104)

Maritime Risk Evaluation and Safety Optimization in Narrow Straits (M-REASONS): A Case Study in Istanbul Strait and English Channel

Theme: Risk Evaluation and Safety Optimization in the Maritime Industry

By
Liverpool Logistics, Offshore and Marine (LOOM) Research Institute,
Liverpool John Moores University (LJMU)

August 2022

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International Association of Maritime Universities

This report is published as part of the 2021 Research Project in the 2021 Capacity Building Project of International Association of Maritime Universities, which is fully supported by The Nippon Foundation.

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Published by the International Association of Maritime Universities (IAMU) Secretariat
Meiwa Building 8F, 1-15-10 Toranomon, Minato-ku,
Tokyo 105-0001, JAPAN
TEL : 81-3-6257-1812 E-mail : info@iamu-edu.org URL : http://www.iamu-edu.org

ISBN978-4-907408-41-1

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Abstract This research aims to assist with navigational safety by investigating marine accidents and identifying the high-risk areas in terms of grounding and collision-contact for the Dover Strait and Istanbul Strait. The identification of high-risk areas is conducted through spatial analysis to determine accident "hot spots" where grounding and collision-contact accidents are more highly concentrated. Given that marine accident data can be incomplete, industrial experts will be used to bridge the data gaps. The identification of high-risk areas will allow for the evaluation of the existing RCMs for narrow waterways. Thus, comparisons between the two outlined areas can be made and the RCMs can be ranked based upon their suitability by region. In terms of the industrial perspective, the results of the results of the RCM ranking will instigate the development of guidelines for the EC and IS in terms of navigational safety. These RCMs are tested in a simulator environment with ocean going seafarers.

Keyword: *Risk Analysis, Safety Assessment, Navigational Safety, Narrow Waterways, Traffic Management*

1 Introduction

Marine accidents, especially in terms of grounding and collision-contact, have always been a major concern. Many accidents 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. Considering these studies some of the main causes of collision-contact accidents can be listed as: violation of COLREG, inappropriate lookout, ineffective use of bridge navigation equipment, poor visibility and heavy traffic [1, 2, 3, 4, 5, 6]. Similarly, some identified causes of grounding accidents include improper passage planning, position fixing errors, inappropriate chart usage, fatigue, heavy weather and heavy sea conditions [4, 5, 6, 7, 8]. Yet marine accidents continue to occur in relatively high numbers. Between 2008 and 2017 the MAIB identified 102 accidents in UK waters, where 58% where either collision-contact or grounding [9]. Furthermore, a study conducted by LJMU and KTU identified that 60% of grounding and collision-contact accidents, around the IS, occurred in shallow waters, less than 12 miles from the coast. Narrow waterways fall into the criteria of short distances from the coast, heavy traffic, and potential shallow waters, as with the EC and IS. Therefore, the issue of identification of high-risk areas in terms of marine accidents in narrow waterways needs to be addressed as well as precautions for the prevention of these accidents.

1.1 Marine Accident Analysis Background

Coastal areas, especially narrow waterways, are regions where marine accidents frequently occur [10, 11, 12, 13, 14] Despite the developments in maritime technology and the international safety rules that have come into force, marine accidents continue to occur in narrow waterways and are a serious threat in the maritime industry [15, 16, 17] According to the European Maritime Safety Agency (EMSA) data, approximately 3,000 marine accidents occurred annually between the years 2015-2020. In this period, the decrease in the number of accidents between two consecutive years does not reach more than 7%. The fact that accidents could not be prevented at the targeted level on a global scale makes the effectiveness of the measures taken against accidents somewhat questionable [3, 18, 19]. In narrow waterways, traffic separation lines, pilotage services, and vessel traffic services are essential applications that ensure navigational safety [20, 21]. On the other hand, local traffic, strong currents, sharp turns, intense glare from the Sun, marine topography, the inadequacy of anchorage areas, and transit ship traffic are the main factors that threaten the safety of navigation on narrow waterways [22, 23, 24]

The Istanbul Strait (IS) and the Dover Strait (DS) are important and dangerous narrow waterways for maritime trade. Accidents and the factors that cause accidents in these narrow waterways are variable in nature [25]. Intensifying ship traffic day by day brings potential accident risks [26, 27]. Therefore, it is necessary to identify reoccurring and variable risks in narrow waterways and determine relevant risk control options, to ensure sustainable maritime trade. Every year, approximately 150,000 ships pass through DS and 50,000 ships through IS [28]. Between 2011 and 2018, 2,370 marine accidents occurred in the whole English Channel area and 106 marine accidents in the Turkish Straits, including the IS [29]. Numerical data and academic studies have proven that IS and DS are hazardous navigational areas.

The most common accident types among marine accidents are collision, contact, sinking and grounding [3, 8, 30, 31, 32]. These marine accidents also occur frequently in narrow waterways. All four accident types are closely related to the structure of narrow channels, traffic density and environmental conditions [12, 25] Therefore, this study focuses on these specific accident types (collision, contact, sinking and grounding).

IS has been studied frequently due to its strategic importance and geographical location. In his study, [33] determined the risky sea areas and revealed the associated risks by conducting a spatial analysis of 461 marine accidents that occurred in IS between the years 1953-2002. Arslan and Turan (2009) [34] revealed the factors affecting the occurrence of marine accidents in the IS utilizing the Analytic Hierarchy Process (AHP) and Strength, Weakness, Opportunity, Threat (SWOT) analysis methods. Aydogdu et al. (2012) [26] observed the effect of local traffic on the Istanbul Strait by performing Marine Traffic Fast Time Simulation modelling in his study. Uğurlu et al. (2016b) [13] evaluated marine accidents in the Istanbul Strait regarding economic loss and death/injury. Similarly, Aydogdu (2014) [35], determined the dangerous areas and threats at the southern entrance of the Istanbul Strait in terms of ship traffic with the Generic AHP model.

By comparison to the IS, the number of studies related to marine accidents in DS is very limited. Roberts (2008) [36], in his study, examined the fatal accidents that occurred on British merchant ships between 1919 and 2005, and revealed the main causes of death in the area. These are listed as sinking in storms or heavy weather, fires and explosions in holds, and collisions in restricted visibility. As a result, he emphasized that the innovations made in the field of occupational health and safety reduce the deaths caused by accidents. Squire (2003) [12] examined the relationship between ship accidents and ship traffic in DS. As a result of the study, the causes of accidents in DS were revealed and recommendations were made to prevent them. It was emphasized that violations of the International Regulations for Preventing Collisions at Sea (COLREG) have a great impact on accidents and the Traffic Separation Schemes (TSS) structure also plays an active role in the occurrence of accidents.

On 20 March 2018, a collision occurred between a Maltese flagged general cargo vessel and a Belgian flagged fishing vessel in DS. As a result of the accident, the fishing vessel completely sank, and all crew were rescued by search and rescue operation. The general cargo vessel was damaged at the bow [37] On 7 April 2018, at the Beylerbeyi (in the sector Kandilli) in IS, a Maltese flagged 225-meters bulk carrier contacted the shore due to rudder failure. The total cost of the accident to the shipping company, including the damage to coastal structures, was over $50 million [38]. These and similar marine accidents, which have recently occurred in both narrow waterways, prove that the safety measures taken in narrow waterways should potentially be reconsidered. Determining risky sea areas in narrow waterways with high traffic density, identifying current risks, and reviewing existing safety measures are important for countries adjacent to narrow waterways and other parties of the maritime industry.

1.1.1 Marine Accident Contributing Factors

Accidents occur due to several factors which include but are not limited to those outlined as follows. However, these are considered key root causes of marine accidents.

Fatigue: This comes because of overloading individuals with heavy work functions depriving them of their regular resting periods due to operational demands and or commercial pressures especially when the ship is under-manned, or improper schedules of operations or tasks [38, 39, 40]

Distractions: In this factor there are issues such as, paperwork, technological influence, human behavior in relation to peripheral movement, personal devices, other crew members and external situations, to name a few [41]. According to UK Marine Accident Investigation Branch (MAIB) investigation reports a collision between the cargo vessel Daroja and oil bunker barge Erin Wood, and the grounding of Attilio Ievoli were due to distractions [42] Navigation is a highly demanding task that must be upheld in high esteem with undivided attention [41, 43].

Reliance on Electronic Navigational Aids: Electronic navigation equipment is used to assist the navigation officer to provide information that will aid his/ her decision-making. Over-reliance on the electronics will not make the decision for the officer-in-charge of the navigational watch nor will it perform the action meant for the Officer on Watch (OOW). Hence, the responsibility of managing the decision-making/taking appropriate actions as deemed safe and practicable for accident-avoidance rests on the OOW [44, 45].

External Influences: This includes weather and sea conditions, as well as the behavior of other vessels. All factors are outside of the control of the crew onboard. Records list cases of vessels colliding at berth, vessels drifting at anchorage, collisions during ship-to-ship operations, and loss to tsunami and surge waves, storms, and sudden heavy weather. In these instances, vessels may not break or breach navigational rules and regulations, but the potential for an accident is ever present [46, 47]. An instance of this occurred in December 2018 when the Russia-registered bulk carrier Kuzma Minin grounded after dragging its anchor in Falmouth Bay, due to wind speeds in excess of 50 knots.

Teammate Influence and Task Deviation: It is perceived that a consistently contributing factor throughout almost all maritime accidents is the human element. The IMO has attempted to address the problem by adopting and amending maritime regulations to regulate the maritime industry. The majority of these regulations have been introduced by two instruments, namely the International Safety Management (ISM) code and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) [48, 49]. Numerous maritime accident investigations have concluded that task deviations by seafarers contributed to many mishaps at sea, such as the grounding and listing of the vessel Hoegh Osaka [50]. Research into investigating the difference between work as imagined and work as it is done in the marine industry is restricted [51, 52]

1.2 Aims and Objectives

The English Channel (EC) and Istanbul strait (IS) are two of the busiest waterways in the world. 42,553 ships passed through the IS in 2016 [53] and 500 vessels use the EC per day [54]. Therefore, this project aims to prepare a safety guide to assist with navigational safety within the EC and IS. The aim of this project shall be accomplished through the following objectives:

- O1: Investigate marine accidents and develop an accident risk map and database for the EC and IS.
- O2: Identify and evaluate the suitability existing Risk Control Measures (RCMs) that apply to narrow waterways.
- O3: Prepare navigation safety guidelines and test their feasibility in a bridge simulator.

O1 will involve an analysis of several marine accident databases and application of ArcGIS. O2 will apply Human Factor Analysis and Classification System (HFACS) and BNs to the accident reports to identify RCMs. Evidential Reasoning (ER) will also be used in O2 to rank RCMs. O3 involves testing suitable RCMs in a simulator to aid the development of the navigational safety guidelines.

2 Spatial Analysis and Risk Map Development

2.1 Geographic Information Systems (GIS) Background

GIS provides the ability to visualise, export and analyse geographic information. Today, GIS software can perform almost any imaginable operation on geographic data and recognise hundreds of different file formats. Due to these features being used for scientific purposes in many fields, including accident analysis [13, 55, 56, 58, 59] GIS is a vital and comprehensive management tool for traffic safety that makes it possible to visualise [59] and interpret accident data on a map [5]. In maritime transport, GIS enables the distribution, classification, and interpretation of multiple accident data points on a digital map [13, 60]

GIS is a helpful tool for analysing marine accidents as it allows the processing of both spatial data and attributes data. In this study, ArcMap 10.5 is used for spatial density analysis. The Kernel Density Analysis method was preferred to transform accident data points into density maps. Kernel Density

Analysis method provides an estimation of probability density function (f(x)) of any continuous random variable (x) by using non-parametric regression analysis. By using the sample data of an event or situation, it reveals the value range function of the probability of this event occurring in a certain neighbourhood. For example, let $x_1, x_2, x_3, \ldots, x_i$ be independently and identically distributed samples (number of accidents in a given area). The density distribution function $\hat{f}_h(x)$ of these samples is calculated as follows [61, 62].

$$\hat{f}_h(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right) \tag{1}$$

where;

$\hat{f}_h(x)$: Kernel density distribution function

K : Kernel Function with symmetric probability density function and not a negative value

h : Correction parameter called search radius (bandwidth); should always be h>0, but the dataset should be kept as small as it allows

n : Sample size

x : Kernel Center (origin of the specified location for analysis)

x_i : ith sample

x-x_i : Distance between Kernel Center and sample value (distance)

2.2 *Spatial Analysis Methodology*

n this study, spatial and statistical analyses were constructed with ship accidents within the traffic separation schemes in 2 narrow waterways (IS and DS). Kernel Density estimation method was used in spatial analysis of accident data, and Chi-Square independence test was used in the statistical analysis of the data. The results of the analyses were shared and interpreted with experts from the sector who have the necessary knowledge and experience in IS and DS. The study was completed in five consecutive steps (Figure 1).

2.3 *Obtaining accident reports and preparation of the dataset*

In the first step of the study, a database containing spatial and attribute data of ship accidents, in IS and DS, was created. Data was collected from 17 different international marine accident databases (Table 1). Accident investigation organisations are members of the International Transport Safety Association (ITSA) and are recognised by many international institutions and organisations, such as IMO and EMSA.

Table 1. Scrutinised marine accident databases

Country	Name	Abbreviation
Australia	Australian Transport Safety Bureau	ATSB
Canada	Transportation Safety Board of Canada	TSB
IMO	Global Integrated Shipping Information System	GISIS
Finland	Safety Investigation Authority	SIA
France	Civil Aviation Safety Investigation and Analysis Bureau	BEA
Europe	European Maritime Safety Agency	EMSA
Japan	Japan Transport Safety Board	JTSB
Netherlands	Dutch Safety Board	DSB
New Zealand	Transport Accident Investigation Commisssion	TAIC
Norway	Accident Investigation Board Norway	AIBN
Russia	Interstate Aviation Committee	IAC
Singapore	Air Accident Investigation Bureau of Singapore	AAIB

Sweden	Swedish Accident Investigation Authority	SAIA
China	Aviation Safety Council	ASC
Turkey	Transport Safety Investigation Center	UEIM
United Kingdom	Marine Accident Investigation Board	MAIB
United States	National Transportation Safety Board	NTSB

In accordance with the scope of the study, a total of 6,548 accident data that occurred in the 16-year period between 01.01.2004 and 01.01.2020 were scrutinised. Of these accidents, 5,175 accidents were obtained from the GISIS database [63], 944 accidents from the MAIB database [64], and 429 accidents from the UEIM database [65]. Each accident's spatial information (Global Positioning System (GPS) data) was then positioned on the electronic chart and was reviewed as to whether the accident would be included in the data set of the study. Following the spatial analysis, the various accident types were examined. Since collision, contact, grounding and sinking accidents will be examined within the scope of the study, the accidents that occurred in other categories were excluded from the data set of the study. As a result, 274 (IS:240, DS:34) out of 6,548 marine accidents were taken as the data set to be used in the study. In all of these accidents, at least one of the ships involved is subject to IMO regulations (vessels of 500 gross tonnage and above).

2.4 Spatial analysis of accidents and identification of hot areas

At this step, the hot spot areas where accidents are concentrated were determined by using the Kernel Density Analysis method and a marine accident density map was created for each narrow waterway. Raster nautical charts were preferred to interpret anchor points, traffic separation schemes, lighthouses, buoys, and geographical shapes in the density map created for narrow waterways [66, 67]. The primary purpose of Kernel Density Analysis is to generate density distribution maps in the desired search radius from the core points where the accidents occur [68]. The search radius is required to calculate Kernel densities in the geographic area where accidents (point data) are located. Conceptually, it is assumed that there is a uniform area around each accident within the distance of the search radius (Figure 2a) [61]. The Kernel density value is the highest in the centre of the accident and decreases with distance, thus the Kernel density value reaches zero at the far end of the search radius distance (Figure 2b). When calculating the Kernel density value in each output raster cell (in the grid) (Equation 1), the sum of the Kernel density values formed around all the point data affecting that cell is taken (Figure 2c). The optimum selection of the Kernel search radius is very important for accurately detecting dense areas [69]. If the search radius is defined too high, non-dense areas will also come out as "high density". If the search radius is specified as too low, then hot spots will be detected instead of dense areas (Figure 2d). Both selections will create erroneous results, and that leads to incorrect implications. For applying Kernel Density Analysis in the study, kernel radii were optimised by considering other approaches applied in the studies in the literature [61, 70, 71, 73]. Trials in the range of (0.7°×0.7°), (0.5°×0.5°), (0.3°×0.3°), (0.1°×0.1°), (0.09°×0.09°), (0.07°×0.07°), (0.05°×0.05°), (0.03°×0.03°), (0.01°×0.01°) were conducted for each narrow waterway. As a result of the application, "Marine Accidents Density Maps" were obtained for both narrow waterways.

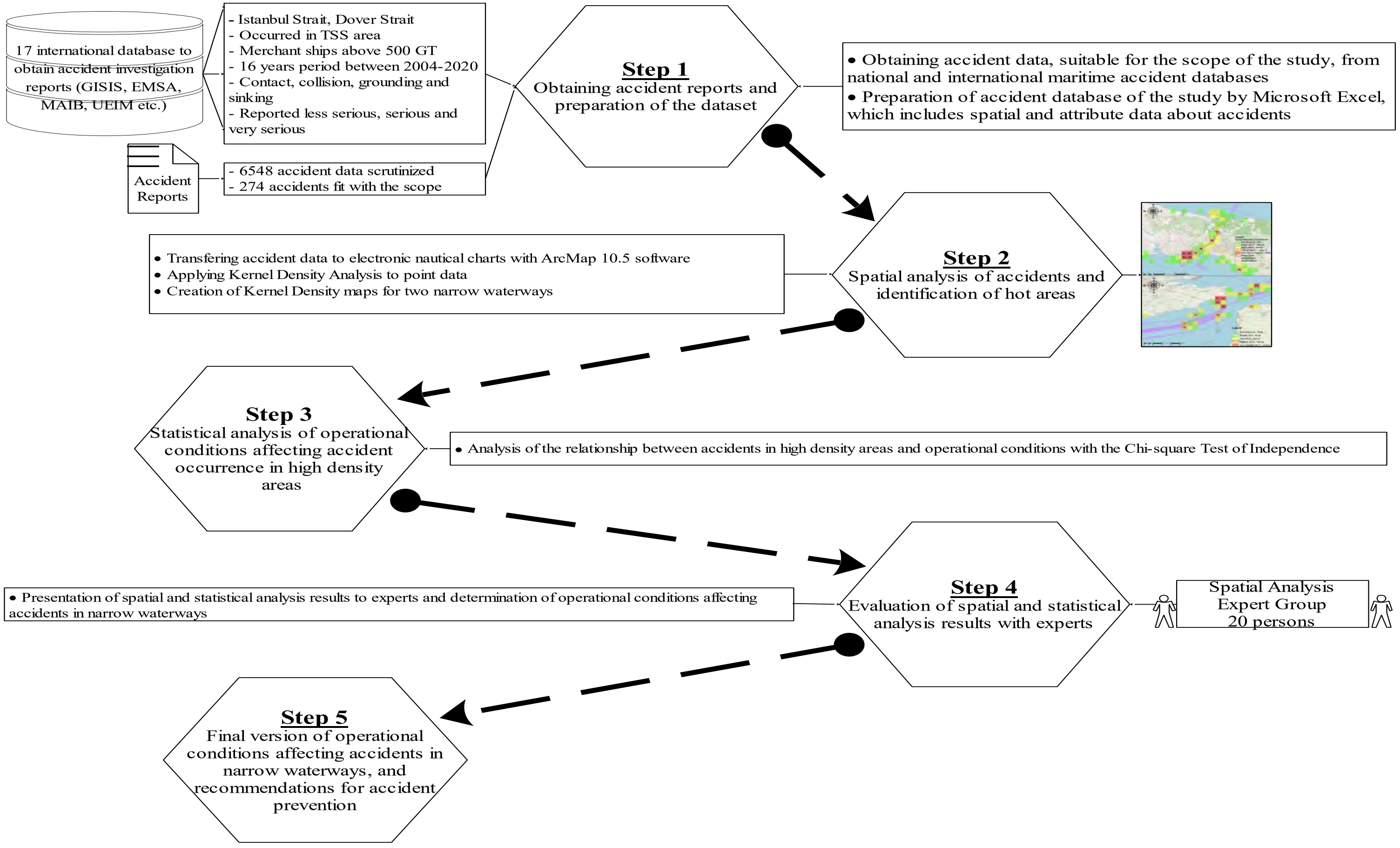
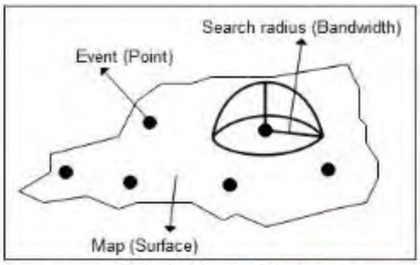
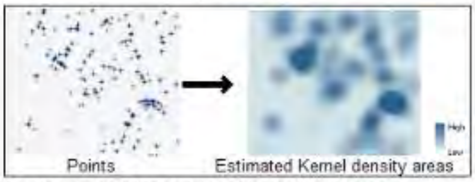


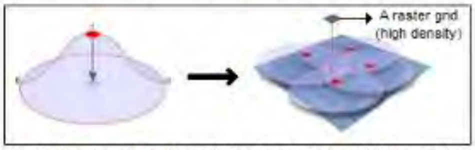
Figure 1. Flow chart of the study



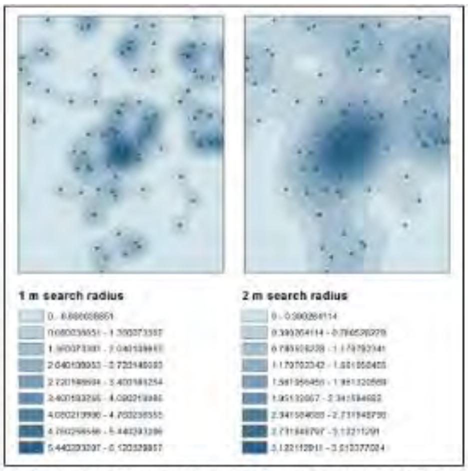
2a. Kernel search radius (bandwidth) of a point



2b. Conversion of point data to Kernel density map



2c. Estimation of the Kernel density of each grid (intersection)



2d. Difference between choosing 1m or 2m of Kernel bandwidth

Figure 2. The basic illustration of the principle of Kernel Density Analysis [69, 75, 76]

2.5 Statistical analysis of operational conditions affecting accident occurrence in high density areas

This stage of the research aims to determine the relationship between operational conditions and accident type, and accident severity and Kernel density. Operational conditions refer to the internal-external environmental factors that the ship is in, both of which play a role in accident formation. Operational conditions play a complementary role in the occurrence of accidents together with unsafe actions (operators' errors and violations). Each accident type, such as collision, contact, grounding, or sinking, contains at least one operational condition (Figure 3) [75, 76].

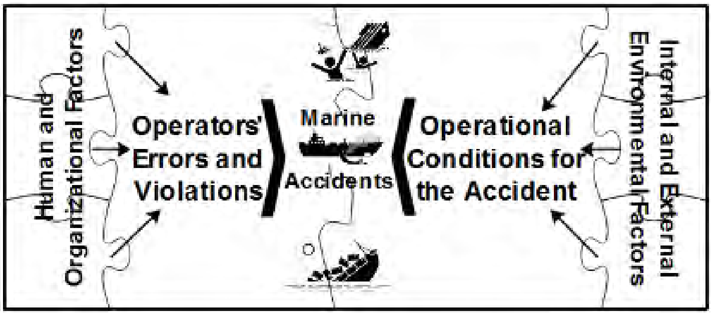


Figure 3. An overview of the formation of marine accident

Chi-Square independence test was used to determine the relationship between operational conditions, accident type and accident severity in "very high density" and "high density" areas. Chi-Square independence test is used to determine whether there is a statistically significant relationship between two variables [77, 78, 79]. One of the most significant advantages of the Chi-Square independence test is that it can be applied to nominal data as well as numerical data [79, 80]. Since the research aim is to examine the relationship between the variables, the Chi-Square independence test has been preferred. The Chi-Square independence test was applied individually for each narrow waterway (IS, DS). First, the significance of the relationship between marine accident types and operational conditions in "very high density" and "high density" areas was analysed for each narrow waterway. Subsequently, the significance of the relationship between accident severity and the operational conditions was examined. Finally, a significant relationship between the Kernel Density of the areas and the operational conditions was tested. Eighteen null hypotheses were established to test the Chi-Square independence (Table 2). IBM Statistical Package for the Social Sciences (SPSS) 25.0 software was used to accurately implement the Chi-Square independence test. As a result of this step, the existence of statistical relationship between accidents in narrow waterways and operational conditions was determined.

Table 2. Chi-Square hypotheses established in the Spatial Analysis study

Hypothesis
$H0_0$: There is no significant relationship between **accident type and age of ship**.
$H0_1$: There is no significant relationship between **accident type and ship size (length).**
$H0_2$: There is no significant relationship between **accident type and type of ship.**
$H0_3$: There is no significant relationship between **accident type and accident severity.**
$H0_4$: There is no significant relationship between **accident type and season.**
$H0_5$: There is no significant relationship between **accident type and day status (day/night).**
$H0_6$: There is no significant relationship between **accident type and Kernel Density.**
$H0_7$: There is no significant relationship between **accident severity and age of ship.**
$H0_8$: There is no significant relationship between **accident severity and ship size (length).**
$H0_9$: There is no significant relationship between **accident severity and type of ship.**
$H0_{10}$: There is no significant relationship between **accident severity and season.**
$H0_{11}$: There is no significant relationship between **accident severity and day status (day/night).**
$H0_{12}$: There is no significant relationship between **accident severity and Kernel Density.**
$H0_{13}$: There is no significant relationship between **Kernel Density and age of ship.**
$H0_{14}$: There is no significant relationship between **Kernel Density and ship size (length).**
$H0_{15}$: There is no significant relationship between **Kernel Density and type of ship.**
$H0_{16}$: There is no significant relationship between **Kernel Density and season.**
$H0_{17}$: There is no significant relationship between **Kernel Density and day status (day/night).**

2.6 Evaluation of spatial and statistical analysis results with experts

In the final stage of the research, the Kernel Density Analysis (Density Maps) and Chi-Square test results are evaluated, along with expert opinions. Each expert was asked to interpret the results of the spatial and statistical analysis by examining the results for each narrow waterway that they have experience of operating in (Table 3). The results of IS were presented to vessel traffic operators and maritime pilots who have worked or currently work in this field. In this way, the results were shared with the industry and the industry's feedback on the research findings was reviewed. For the DS, the results were shared with the oceangoing masters who have passed through this area many times. In the collection of expert opinions, an online interview was conducted with each expert. At the beginning of the interview, the experts were given detailed information about the aims, data set and scope of the study. The Kernel Density Analysis results and Chi-Square test results were then presented to the experts, and they were asked to interpret these results. In this phase of the study, the objective is to reveal the effect of operational conditions on accident formation in "very high density" and "high density" areas where accidents are concentrated. In addition, at this stage, the opinions, and suggestions of the experts regarding existing hazards and the safety measures applied in the IS and DS were received. As a result, recommendations were made to reduce or control the operational hazards in narrow waterways. Detailed information about the experts who participated in the study are as follows:

Oceangoing Master (OM) (3 persons): All oceangoing masters participated in this study have adequate experience and transit through the IS (10-100 times) and DS (10-30 times). Total sea service durations of participated masters vary between 10 and 20 years. One of the participants has been working in the rescue unit of Main Search and Rescue Coordination Center of Turkey for more than 3 years.

VTS Operator (VTSO) (7 persons): All participant VTS operators hold oceangoing master competency. The sea service durations of the participants vary between 5 and 13 years. In addition, participants have more than 3 years of experience as a VTS operators. All of them have passed through IS (20-100 times) and DS (10-90 times). One of the participants is also the former head of the Turkish Vessel Traffic Operators Association.

Maritime Pilot (MP) (4 persons): All participants in this category have experience as a maritime pilot in the Turkish Straits System. All are oceangoing masters, and their sea experience is varies between 10 and 28 years. One of the participants is the former head of Turkish Maritime Pilots' Association. Each of the pilots have passed through the IS (100-1000 times) and DS (10-100 times).

Officials of Istanbul Technical University Turkish Straits Maritime Application and Research Center (ITUBOA) (2 persons): One of the participants is the director of the center. At the same time, they are a seafarer holding Chief Oceangoing Officer (COO) rank and is also a lecturer at Istanbul Technical University. they have many scientific publications in highly recognised, indexed journals (SCI, SSCI, etc.) in the domain of maritime safety, Turkish Straits, and marine accidents. The other participant holds oceangoing master competency and has served as a maritime pilot in the Turkish Straits for more than 30 years. They have held positions as the head of the Turkish Maritime Pilots' Association, EMSA representative, Head of Pilots in Istanbul Strait, Director of Bahçeşehir University Turkish Straits Application and Research Center, Honorary Member of the Turkish Straits Maritime Application and Research Center (ITUBOA), as well as a member of the team that developed the Turkish Straits Traffic Separation Scheme. They were also involved in the planning of anchorage areas of the IS and in the preparation of navigation charts TR292, TR2921 and TR2923.

Marine Accident Investigator (MAI) and Faculty Member in maritime universities (FM) (3 persons): All participants hold a PhD and actively teaching in the field of maritime safety. Sea service duration of the participants varies between 5 and 15 years. Participants have carried out numerous scientific research projects and published manuscripts in highly cited journals, all related to marine accident analysis, maritime safety, and the Turkish Straits.

Chief Officer of Coastal Safety Tug (COCST) (1 person): Participant holds competency of oceangoing master and has 4 years of experience in ship salvage and tug assistance duties in the IS.

Table 3. Experts and demographics

No	Current rank	Experience in current rank (Years)	Previous sea service			Total number of passages		Participation	
			Total (Years)	Last competency	Experience master (Month)	IS	DS	IS (19)	DS (14)
1	FM	8	15	OM	4	>50	>50	+	+
2	FM	9	7	OM	11	>30	>20	+	+
3	OM	5	12	OM	70	>50	>30	+	+
4	VTSO	3	13	OM	24	>50	>90	+	+
5	OM	8	14	OM	96	>30	>20	+	+
6	VTSO	3	13	OM	24	>100	-	+	-

7	OM	6	10	OM	72	>100	>30	+	+
8	COCST	4	8	OM	6	>60	2	+	-
9	VTSO	1	5	COO	-	>50	>20	+	+
10	MP	3	12	OM	48	>100	>20	+	+
11	VTSO	3	7	OM	-	>20	>10	-	+
12	MP	15	28	OM	120	>1000	2	+	-
13	VTSO	6	12	OM	72	>100	>15	+	+
14	MP	9	8	OM	36	>1000	>10	+	+
15	VTSO	2	14	OM	72	>100	>100	+	+
16	MP	16	20	OM	108	>1000	>20	+	+
17	ITUBOA	16	4	COO	-	>30	>5	+	-
18	VTSO	13	20	OM	15	>100	>20	+	-
19	MAI	18	8	OM	12	>30	>5	+	-
20	ITUBOA	30	30	OM	120	>1000	>20	+	+

2.7 Spatial Analysis Results

Spatial analysis, Kernel Density Analysis and Chi-Square independence test results obtained in the study are presented below for IS and DS. The relationship between the accidents in narrow waterways and the operational conditions has been demonstrated based on expert opinions, throughout this section. The operational conditions that should be considered in the risk analysis and safety assessment, which must also be reviewed before each ship passage through narrow waterways, are discussed.

2.8 Istanbul Strait Spatial and Statistical Analysis Results

When the spatial distribution of the accidents in IS is examined, it can be seen that there is a concentration of accidents in anchorage areas (Figure 4). The most common type of accident is collision with 144 accidents. The optimum kernel search radius was determined and applied as 0.03°×0.03°. This was determined by considering the geographical structure of the IS, the location of the sectors, and areas

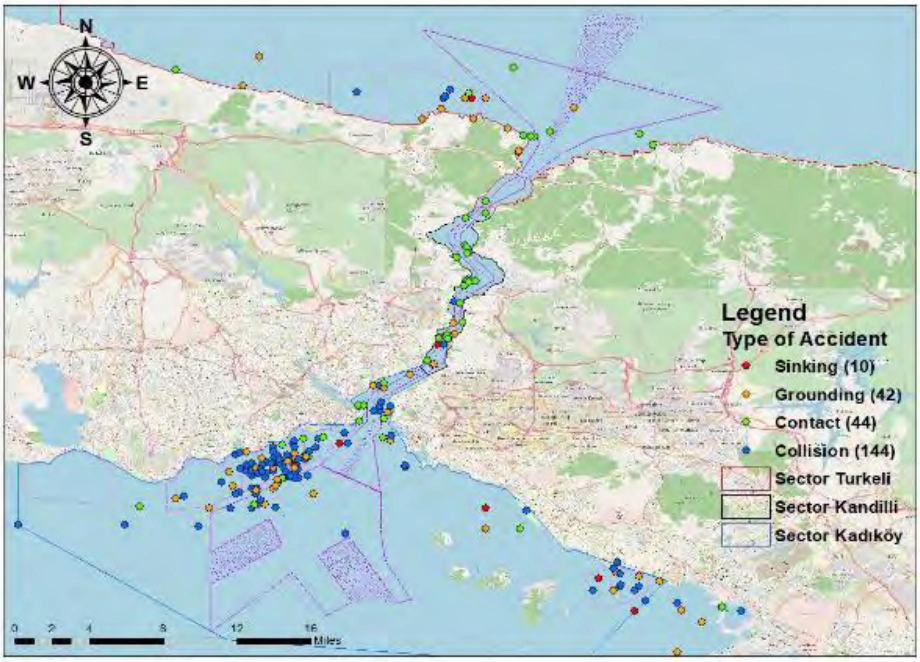


Figure 4. Point distribution map of accidents in IS

where the prevailing current and wind directions change. The areas were divided into five classes (Very high (VH), High (H), Medium (M), Low (L), Very low (VL)) according to the numerical value of their kernel densities. At the end of the application, a Marine Accidents Density Map was obtained for the IS, based on the kernel density value of each grid. There are 4 "very high density" sea areas (90 accidents) and 5 "high density" sea areas (47 accidents) in the IS (Figure 5).

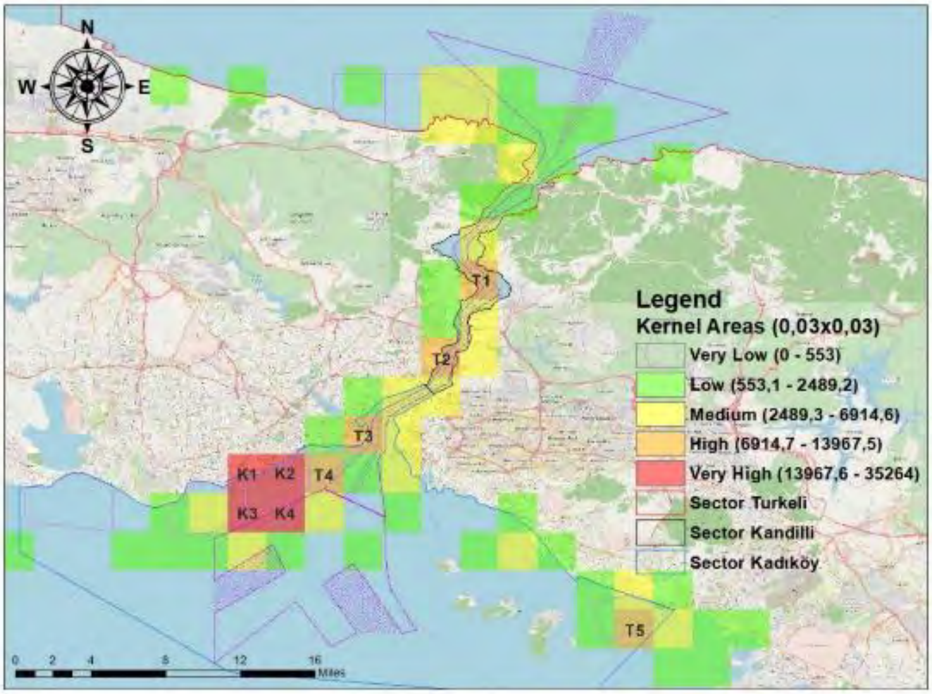


Figure 5. Kernel Density map of IS

A total of 137 marine accidents occurred in "very high density" and "high density" sea areas. According to the spatial distribution of accidents, Sector Kadıköy is the VTS area where ship accidents are most common in IS (Figure 4). All of the "very high density" (K1, K2, K3, K4) areas are around the Ahırkapı anchorage area in Sector Kadıköy (Figure 5). This is where the anchored ships, ships waiting to pass the strait, and the vessels that leave from anchorage to pass the strait are dense. Anchorage area A (T4), the southern entrance of the strait (T3) and anchorage area F (T5) are among the "high density" sea areas in Sector Kadıköy. In addition, 2 areas within the strait itself were identified as “high density” sea areas. The first one is the area (T2) between Umur Banks and Yeniköy, where the current speed (1-3 kts) and direction (S-SW-SE) vary. The other is the Kandilli turning point (T1), the narrowest and most curved part of the IS. The common features of these two "high density" areas within the strait are sharp turns and strong currents. The results of this study confirm the conclusions of previous studies which have determined that the greater risks are posed at the southern entrance of IS (Sector Kadıköy) [26].

Within "very high density" areas, ships between 101-150 meters in length (48.9%), 31 years or older in age(45.6%), and dry cargo ships (85.6%) were found to have the highest percentages of involvement in these accidents. It has been determined that most of the accidents in these “very high density” areas occurred in winter (45.6%) and at night (66.7%). In "high density" areas, the most common ship-related operational conditions were found in vessels of 100 meters or less in length(53.2%), 11-30 years of age (74.5%), and dry cargo type (66.0%). The season and day status of the accidents in these areas are similar to "very high density" areas (Table 4). These results confirm what many literature studies have concluded, which is that night shifts are much riskier than daytime shifts, especially in the areas of anchorage, drift, and traffic participation at the southern entrance of the IS (Akten, 2004; Arslan and Turan, 2009).

Table 4. Distribution of the number of accidents by operational conditions in IS

Operational Conditions		IS (N=240)		IS (VH+H=137)			
				f		%	
		f	%	VH	H	VH	H
Ship Type	Dry Cargo	173	**72.1**	77	31	**85.6**	**66**
	Tanker	22	9.2	1	7	1.1	14.9
	Container Ship	32	13.3	10	8	11.1	17
	Other (RoRo, Passenger, etc.)	13	5.4	2	1	2.2	2.1
Ship Size	Length Overall (LOA)≤100	93	38.8	27	26	30	**55.3**
	101≤LOA≤150	96	**40.0**	44	15	**48.9**	31.9
	151≤LOA	51	21.3	19	6	21.1	12.8
Ship Age	Age≤10	45	18.8	11	5	12.2	10.6
	11≤Age≤30	115	**47.9**	38	25	42.2	**53.2**
	31≤Age	80	33.3	41	17	**45.6**	36.2
Season	Spring	46	19.2	18	5	20	10.6
	Summer	43	17.9	7	13	7.8	27.7
	Autumn	61	25.4	23	14	25.6	29.8
	Winter	90	**37.5**	42	15	**46.7**	**31.9**
Status of the Day	Day (06:01-18:00)	86	35.8	30	21	33.3	44.7
	Night (18:01-06:00)	154	**64.2**	60	26	**66.7**	**55.3**
Accident Type	Grounding	42	17.5	15	8	16.7	17
	Contact	44	18.3	3	19	3.3	**40.4**
	Collision	144	**60.0**	68	17	**75.6**	36.2
	Sinking	10	4.2	4	3	4.4	6.4
Accident Severity	Less Serious	2	0.8	1	0	1.1	0
	Serious	219	**91.3**	82	45	**91.1**	**95.7**
	Very Serious	19	7.9	7	2	7.8	4.3

As a result of the Chi-Square tests for accidents that occurred in "very high density" and "high density" areas in IS, a significant relationship was found between accident type and ship type, accident severity, season and density categories (Table 5). In addition, a significant relationship was determined between kernel density and ship size, ship type and seasons. However, significant relationships were not identified between accident severity and other operational conditions (Table 5).

Table 5. Chi-Square test results of IS

Pairwise Comparisons (Test Hypotheses)		IS	
		Significant Relationship	Significance (*p*)
Accident Type	Ship Age	No	0.103
	Ship Size	No	0.052
	Ship Type	**Yes**	0.015
	Accident Severity	**Yes**	0.001
	Season	**Yes**	0.039
	Status of the Day	No	0.192
	Density of Kernel Area	**Yes**	0.001
Accident Severity	Ship Age	No	0.051
	Ship Size	No	0.052
	Ship Type	No	0.627
	Season	No	0.642

	Status of the Day	No	0.128
	Density of Kernel Area	No	0.555
Density of Kernel Area	Ship Age	No	0.468
	Ship Size	**Yes**	0.015
	Ship Type	**Yes**	0.006
	Season	**Yes**	0.008
	Status of the Day	No	0.192

When accident type and ship type is cross-examined (Table 6), it can be seen that the most common accident types in dry cargo ships are collision (63.0%) and grounding (20.4%). One of the study's remarkable findings is that although container ships are the 4th ranked ship type that makes the most transits according to the IS ship passing statistics, it is the 2nd ranked ship type most frequently involved in the accident statistics. Container ships were mostly involved in the collision (72.2%) and contact (22.2%) accidents in IS (Table 6). Based on the research results, it can be postulated that the high speed of container ships may affect this result. In past studies on narrow waterways, it was revealed that high speed plays an key role in accident formation, especially in collision and contact accidents [80].

When the relationship between accident types and accident severity in IS is examined, 66.7% of "very serious accidents" occurred as a result of sinking and 22.2% as a result of collision accidents. In "serious accidents", collisions had the largest share with 65.4%, in terms of ship type-accident severity, while contacts took second place with 17.3%. These results show that, compared to the results of Wang et al. (2021) [81], a collision accident may have more serious consequences if it occurs in IS.

According to Table 6, when accident type and seasons are cross-examined spring results are similar to winter, whereas autumn results are similar to summer. Accordingly, the most frequent accident types in the spring and winter seasons are collision (52.2% and 66.7%) and grounding (30.4% and 17.5%), respectively. The most frequent collisions (67.6% and 50.0%) and contacts (16.2% and 35.0%) occurred in the autumn and summer seasons. These results clearly show that changing seasonal conditions also affect accident types. In addition, it has been observed that at least half of the accidents that occur in every season in IS are collision accidents. This result shows that traffic density in IS is always one of the highest risks in the area and is in concurrence with previous studies [26, 34, 35]

When accident type and Kernel categories (“high” and “very high”) are analysed (Table 7), it can be seen that collision accidents (75.6%) have a very high share in "very high density" areas. It is also shown in Figure 5 that the "very high density" areas (K1 – K4) are in and around the Ahırkapı anchorage area. The main reason for such a high collision rate is the ships' anchoring without sufficient distance due to congested anchorage areas. In "high density" areas, contact (40.4%) and collision (36.2%) accidents are the most frequent accident types. Similarly, it is postulated that the strong currents, in these areas, are a key factor in vessels being involved in contact situations. When Figures 4 and 5 are considered together, it is seen that contact accidents are mostly concentrated in the areas where the current speed is highest. Ships that cannot maintain sufficient steering control in these areas, which also have sharp turns, face the danger of running adrift and aground. In past studies, it has been reported that the risk of accidents increases in areas where there are strong and variable currents, at sharp turning points [33, 82]. These results are very useful for understanding which types of accidents and hazards are most likely in specific areas of the IS.

According to the Chi-Square test results (Table 5), no significant relationship was found between the accident severity and the operational conditions. Therefore, in this study, it cannot be concluded that "increasing ship length also increases the severity of accidents in IS", as stated in the study conducted by [83].

When the Kernel density categories and ship size are cross-examined (Table 8), there was no significant difference identified in the distribution of accidents involved ships of 100 meters or less in length by density category. However, it was determined that 3 out of every 4 accidents in ships over 100 meters were in "very high density" areas. Considering that the "very high density" areas are around the anchorage area, these results are evidence of congestion at anchorage and that ships are anchored without a sufficient safe distance between them [25].

While dry cargo, container and other types of ships were mostly involved in accidents in "very high density" areas, tanker vessels were mostly involved in "high density" areas. The low accident rate in the "very high density" areas involving tankers, which are the 2nd ranked ship type that makes the most transits from the IS, may be related to the fact that personnel working on such ships may pay more attention to safety warnings. The risk perception and understanding of safety culture of employees in different industries were compared by Nævestad et al. (2019) [84]. the study showed that crew members on tanker vessels are less likely to compromise safety when compared to crew on other types of ships.

When the relationship between the seasons and the density category is examined, it has been observed that accidents occurring in spring, autumn, and winter were mostly in "very high density" areas. On the other hand, the rate of accidents in summer was higher in "high density" areas. It is known that the weather and sea conditions in IS in summer are calmer and more stable than in other seasons. These results reveal the effect of changing seasonal conditions on accidents and support the results of previous studies [34, 83].

Table 6. Cross-table between accident type and ship type, accident severity for IS

			Ship Type				Accident Severity		
			Dry Cargo	Tanker	Container Ship	Other	Less Serious	Serious	Very Serious
Accident Type	Grounding	Number	22	1	0	0	1	21	1
		Accident Type (%)	95.7	4.3	0.0	0.0	4.3	91.3	4.3
		Ship Type-Accident Severity (%)	**20.4**	12.5	0.0	0.0	100.0	16.5	11.1
	Contact	Number	12	5	4	1	0	22	0
		Accident Type (%)	54.5	22.7	18.2	4.5	0.0	100.0	0.0
		Ship Type-Accident Severity (%)	11.1	62.5	**22.2**	33.3	0.0	**17.3**	0.0
	Collision	Number	68	2	13	2	0	83	2
		Accident Type (%)	80.0	2.40	15.3	2.4	0.0	97.6	2.4
		Ship Type-Accident Severity (%)	**63.0**	25.0	**72.2**	66.7	0.0	**65.4**	**22.2**
	Sinking	Number	6	0	1	0	0	1	6
		Accident Type (%)	85.7	0.0	14.3	0.0	0.0	14.3	85.7
		Ship Type-Accident Severity (%)	5.6	0.0	5.6	0.0	0.0	0.8	**66.7**
Total		Number	108	8	18	3	1	127	9
		Accident Type (%)	78.8	5.8	13.1	2.2	0.7	92.7	6.6

Table 7. Cross-table between accident type and season, the density of Kernel area for IS

			Season				Density of Kernel Area	
			Spring	Summer	Autumn	Winter	High	Very High
Accident Type	Grounding	Number	7	1	5	10	8	15
		Accident Type (%)	30.4	4.3	21.7	43.5	34.8	65.2
		Season-Accident Severity (%)	**30.4**	5.0	13.5	**17.5**	17.0	16.7
	Contact	Number	1	7	6	8	19	3
		Accident Type (%)	4.5	31.8	27.3	36.4	86.4	13.6
		Season-Accident Severity (%)	4.3	**35.0**	**16.2**	14.0	**40.4**	3.3
	Collision	Number	12	10	25	38	17	68
		Accident Type (%)	14.1	11.8	29.4	44.7	20.0	80.0
		Season-Accident Severity (%)	**52.2**	**50.0**	**67.6**	**66.7**	**36.2**	**75.6**
	Sinking	Number	3	2	1	1	3	4
		Accident Type (%)	42.9	28.6	14.3	14.3	42.9	57.1
		Season-Accident Severity (%)	13.0	10.0	2.7	1.8	6.4	4.4
Total		Number	23	20	37	57	47	90
		Accident Type (%)	16.8	14.6	27.0	41.6	34.3	65.7

Table 8. Cross-table between the density of Kernel area and ship size, ship type, the season for IS

			Ship Size (m)			Ship Type				Season			
			30-100	**101-150**	**151≤**	**Dry Cargo**	**Tanker**	**Container Ship**	**Other**	**Spring**	**Summer**	**Autumn**	**Winter**
Density of Kernel Area	High	Number	26	15	6	31	7	8	1	5	13	14	15
		Density of Kernel area (%)	55.3	31.9	12.8	66.0	14.9	17.0	2.1	10.6	27.7	29.8	31.9
		Ship Size-Season (%)	**49.1**	25.4	24.0	28.7	**87.5**	44.4	33.3	21.7	**65.0**	37.8	26.3
	Very High	Number	27	44	19	77	1	10	2	18	7	23	42
		Density of Kernel area (%)	30.0	48.9	21.1	85.6	1.1	11.1	2.2	20.0	7.8	25.6	46.7
		Ship Size-Season (%)	**50.9**	**74.6**	**76.0**	**71.3**	12.5	55.6	66.7	**78.3**	35.0	**62.2**	**73.7**
Total		Number	53	59	25	108	8	18	3	23	20	37	57
		Density of Kernel area (%)	38.7	43.1	18.2	78.8	5.8	13.1	2.2	16.8	14.6	27.0	41.6

The results of the study for IS (Chi-Square and spatial analysis) were presented to the experts and they were asked to evaluate the impact of each operational condition on the accidents that occurred in the IS. The evaluations of 19 experts who are competent in the IS regarding the study are presented in Figure 6.

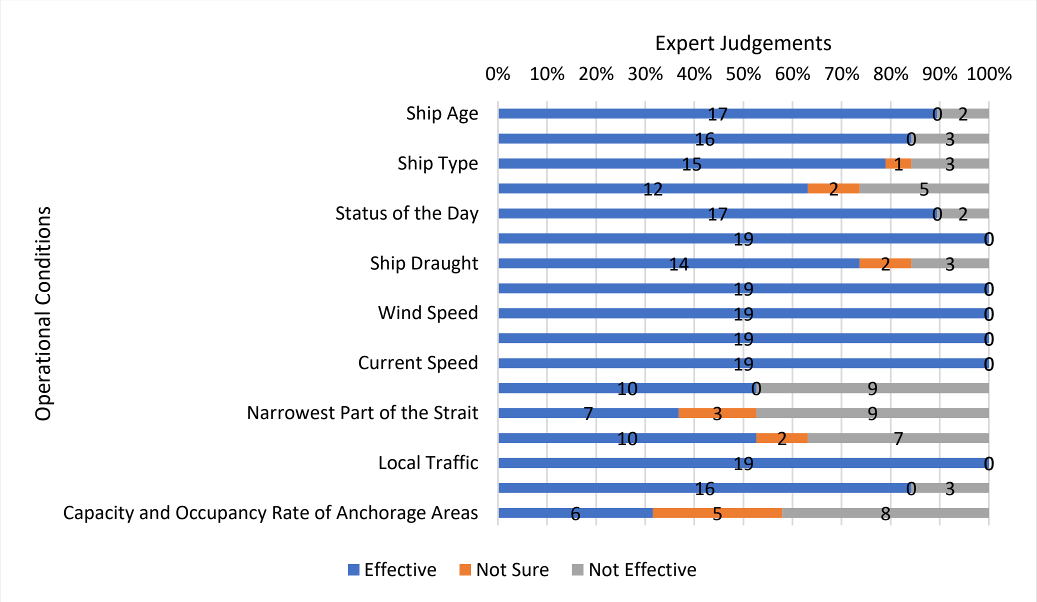


Figure 6. Expert judgements for operational conditions in IS.

2.9 *Dover Strait Spatial and Statistical Analysis Results*

In the DS, one of the busiest narrow waterways in the world, accidents are concentrated at the north of the traffic separation lines and at each entrance to the strait. In addition to this, it is understood that accidents are intense on the ferry line between Dover and Calais (Figure 7). Collision and grounding are the most common accident types in DS (Table 9). The optimum kernel search radius was determined as 0.09˚×0.09˚, considering the geographical structure of the Dover Strait, the traffic separation scheme, the size of the radar monitoring area and the spatial distribution of the accidents. A Marine Accidents Density Map is obtained based on kernel density values for DS and is presented in Figure 8. Five "very high density" sea areas and 8 "high density" sea areas were identified in DS. 71% of the accidents examined in DS occurred in these two categories of sea area.

Off the coast of Dover, are the areas where the domestic sea traffic is intense and the safe waterway is narrowed (K2, K3, K4), and the area containing the Varne Bank (K5) are the "very high density" sea areas. In addition to these, the vicinity of the Foxtrot 3 buoy (K1) was also identified as one of the "very high density" areas in the DS (Figure 8). This area is an area where traffic is multidirectional and the buoy acts as a junction. The "high density" sea areas in the DS are highly scattered and spread across the entire strait. "High density" areas are mostly located in the middle of the southern approach (T6, T7, T8) and northern approach (T1, T2, T3, T5) separation lines. The only exception is the area at the exit of the Port of Calais (T4) (Figure 8). In this area, ferry traffic is heavy, and the safe waterway is very limited. The findings of this study are consistent with Squire's (2003) [12] study. Squire (2003) [12] concluded that half of the accidents in the DS occurred at the bottleneck between South Falls - Varne and most of the accidents occurred in the northern part of the separation line.

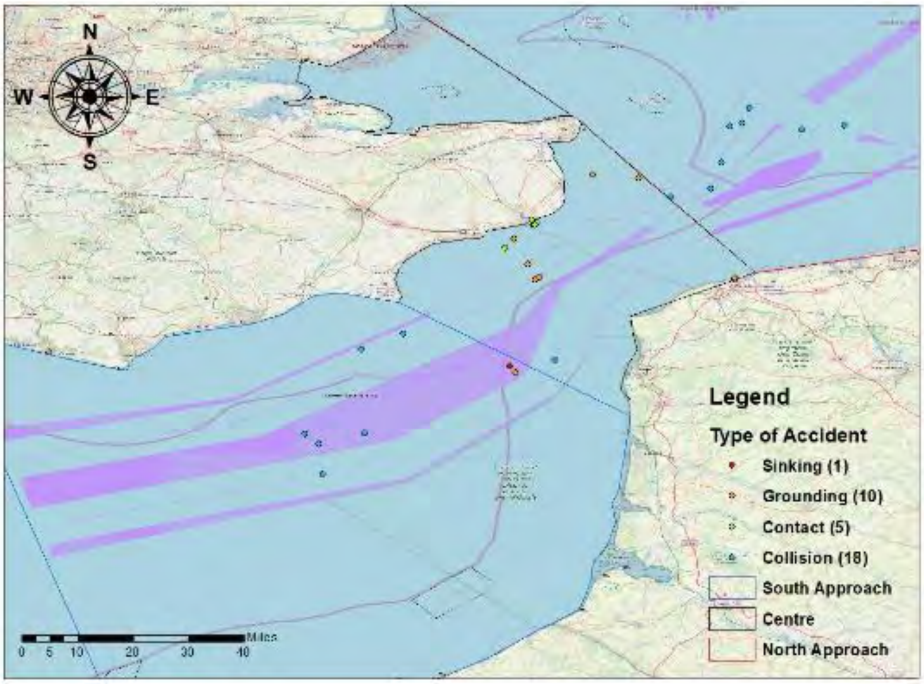


Figure 7. Point distribution map of accidents in Dover Strait

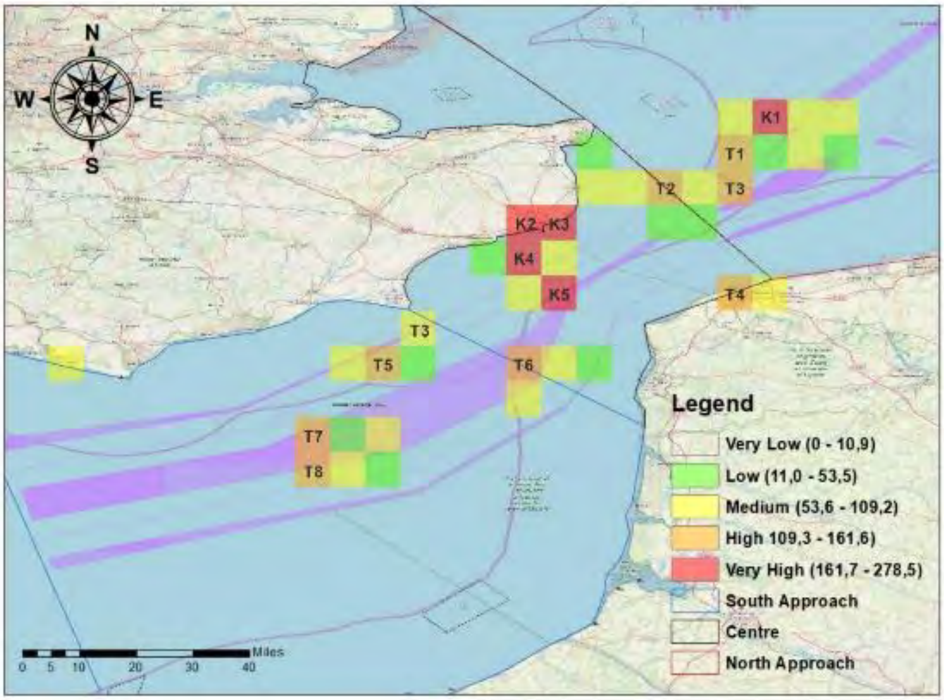


Figure 8. Kernel density map of Dover Strait

In the DS, the ship type most frequently involved in accidents in "very high density" areas is the "other" category, which also includes ferries, while dry cargo ships are in second place. In "high density" areas, container ships are the most frequently involved in accidents, while the "other" category is in the second. More than 100 reciprocal ferry services operate in DS every day [85]. The heavy ferry traffic in the region has had an impact on the accident numbers to bring the "other" category to the fore in accidents in both "very high density" and "high density" regions.

The factors of ship size and ship age encountered in accidents in the DS are similar in "very high density" and "high density" areas. In both areas, ships over 150 meters (81.8% and 61.5%, respectively), 10 years and under (81.8% and 53.8%, respectively) are the most common ship-related operational conditions in accidents. Ships transiting the DS are larger than ships transiting IS. This is the main reason for the difference in ship size between the accidents on the two narrow waterways.

Accidents in "very high density" areas occurred mostly in winter (36.4%) and during daytime (54.5%). In "high density" areas, the most accidents occurred in spring (38.5%) and winter (38.5%) and at night (61.5%) (Table 9). In the northern high latitudes, harsher weather and sea conditions prevail in winter than in summer. The results are consistent, as bad weather and sea conditions adversely affect safe navigation, especially in areas where the strait is narrow, and shallows are dense.

Table 9. Distribution of accidents in Dover Strait by operational conditions

Operational Conditions		**DS (N=34)**		**DS (VH+H=24)**			
				f		***%***	
		f	***%***	**VH**	**H**	**VH**	**H**
Ship Type	Dry Cargo	6	17.6	3	1	**27.3**	7.7
	Tanker	5	14.7	2	2	18.2	15.4
	Container Ship	10	**29.4**	2	6	18.2	**46.2**
	Other (RoRo, Passenger, etc.)	13	38.2	4	4	**36.4**	**30.8**
Ship Size	Length Overall (LOA)≤100	4	11.8	1	1	9.1	7.7
	101≤LOA≤150	7	20.6	1	4	9.1	30.8
	151≤LOA	23	**67.6**	9	8	**81.8**	**61.5**
Ship Age	Age≤10	18	**52.9**	9	7	**81.8**	**53.8**
	11≤Age≤30	16	47.1	2	6	18.2	46.2
	31≤Age	0	0.0	0	0	0	0
Season	Spring	8	23.5	2	5	18.2	**38.5**
	Summer	7	20.6	2	2	18.2	15.4
	Autumn	6	17.6	3	1	27.3	7.7
	Winter	13	**38.2**	4	5	**36.4**	**38.5**
Status of the Day	Day (06:01-1800)	15	44.1	6	5	**54.5**	38.5
	Night (18:01-06:00)	19	**55.9**	5	8	45.5	**61.5**
Accident Type	Grounding	10	29.4	5	3	**45.5**	**23.1**
	Contact	5	14.7	4	1	**36.4**	7.7
	Collision	18	**52.9**	2	8	18.2	**61.5**
	Sinking	1	2.9	0	1	0	7.7
Accident Severity	Less Serious	10	29.4	5	5	45.5	38.5
	Serious	19	**55.9**	6	6	**54.5**	**46.2**
	Very Serious	5	14.7	0	2	0	15.4

Unlike in IS, the most common accident types in DS in "very high density" areas were grounding (45.5%) and contact (36.4%) accidents, respectively. In "high density" areas, collision (61.5%) and grounding (23.1%) accidents were observed most frequently (Table 9). As a result of Chi-Square tests for accidents occurring in "very high density" and "high density" areas in the DS, significant relationships ($p<0.05$) were found between accident type-ship size and accident severity-ship size. No significant relationship was found between the density category of the geographical areas where the accidents occurred and the operational conditions (Table 10).

Table 10. Chi-Square test results of DS

Pairwise Comparisons (Test Hypotheses)		DS	
		Significant Relationship	**Significance (*p*)**
Accident Type	Ship Age	No	0.397
	Ship Size	**Yes**	0.016
	Ship Type	No	0.077
	Accident Severity	No	0.054
	Season	No	0.516
	Status of the Day	No	0.368
	Density of Kernel Area	No	0.393
Accident Severity	Ship Age	No	0.122
	Ship Size	**Yes**	0.002
	Ship Type	No	0.330
	Season	No	0.067
	Status of the Day	No	0.411
	Density of Kernel Area	No	0.397
Yoğunluk	Ship Age	No	0.148
	Ship Size	No	0.203
	Ship Type	No	0.415
	Season	No	0.523
	Status of the Day	No	0.431

When accident type and ship size is cross-examined (Table 11), ships under 101 m were involved in contact (50.0%) and sinking (50.0%) accidents, although they were few in number. Ships with a length of 101-150 meters are riskier in terms of grounding (60.0%) and collision (40.0%). 70-80% of the ships passing through the DS are ships larger than 150 meters. Ships over 150 meters were mostly involved in collision (47.1%) and grounding (29.4%) accidents. These results show that there is a correspondence between the size of the ships passing through the area and the ships involved in the accidents. When the relationship between accident severity and ship size is examined, it is seen that 66.7% of accidents resulted as "very serious" in ships under 101 meters. On the other hand, 66.7% of the accidents resulted as "less serious" in ships with a length of 101-150 meters. In ships of 151 meters and above, where accidents occurred most frequently, 61.1% of the accidents resulted as "serious". These results show that there are varying risks depending on the size of the ships that pass through the DS.

Table 11. Cross-table between accident type-ship size and accident severity-ship size for DS

			Ship Length (m)		
			30-100	101-150	151≤
Accident Type	Grounding	Number	0	3	5
		Accident Type (%)	0.0	37.5	62.5
		Ship Size (%)	0.0	**60.0**	**29.4**
	Contact	Number	1	0	4
		Accident Type (%)	20.0	0.0	80.0
		Ship Size (%)	**50.0**	0.0	23.5
	Collision	Number	0	2	8
		Accident Type (%)	0.0	20.0	80.0
		Ship Size (%)	0.0	**40.0**	**47.1**
	Sinking	Number	1	0	0
		Accident Type (%)	100.0	0.0	0.0
		Ship Size (%)	**50.0**	0.0	0.0
Acci-	Less Serious	Number	1	2	7
		Accident Severity (%)	10.0	20.0	70.0

	Ship Size (%)	33.3	**66.7**	38.9
Serious	Number	0	1	11
	Accident Severity (%)	0.0	8.3	91.7
	Ship Size (%)	0.0	33.3	**61.1**
Very Serious	Number	2	0	0
	Accident Severity (%)	100.0	0.0	0.0
	Ship Size (%)	**66.7**	0.0	0.0

The results of the study for DS (Chi-Square and spatial analysis) were presented to the experts and they were asked to evaluate the impact of each operational condition on the accidents that occurred in the DS. The evaluations made by 14 experts who are competent in the DS are given in Figure 9.

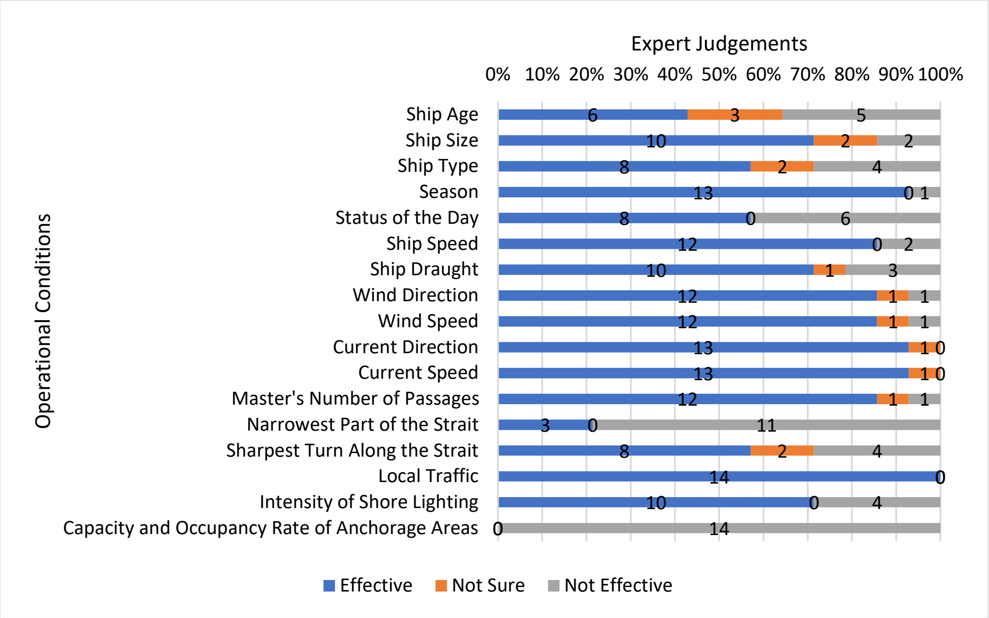


Figure 9. Expert judgements for operational conditions in DS

2.10 Spatial Analysis Conclusions

When the expert opinions and the results of the study are evaluated together, it is understood that there is a relationship between the accidents that occurred in narrow waterways and the operational conditions examined. Thus, ship-specific risks should be evaluated as well as risks specific to the narrow waterway (area), while evaluating the risks that threaten safety in narrow waterways. In the light of the results of the study, it is important to determine the risk factors arising from the operational conditions (ship size, ship type, ship age, transit time, VTS Sector, traffic density) specific to each of the vessels making passages through narrow waterways, in order to increase and maintain the safety of navigation. In addition, given the statistical data, it is necessary to determine the risk factors arising from the operational conditions (narrowest part of the channel, density categories and numbers, seasonal risk, day status) specific to each narrow waterway (IS, DS, etc.). The channel passing operation should be dynamically planned for each ship and each narrow waterway. Risk analysis of each passage should be done meticulously for each ship that will enter the channel. The numerical results to be obtained from these analyses may also be considered while deciding compulsory pilotage and compulsory tugboat escort.

3 Identification of risk factors through HFACS-PV

3.1 Human Factor Analysis and Classification System (HFACS)

HFACS based on Reason's Swiss Cheese model was first used by Wiegmann and Shappell [86] for the analysis of aviation accidents. It is a general human error analysis method, and it allows for the investigation of accident occurrences in a hierarchical structure. With this method, it is possible to examine the effects of human factors on accidents and to elaborate the relevant active failures and latent conditions. The most important feature that distinguishes HFACS from other accident analysis methods is its comprehensive taxonomy for the analysis of human and organizational factors [86]. With this taxonomy, human and organizational factors can be easily and accurately extracted in complex events such as accidents [87, 88]. In the classic HFACS structure, the causes of accidents are examined at four levels respectively: ; organizational influence, unsafe supervision, pre-condition for unsafe act and unsafe act (Figure 10) [89, 90].

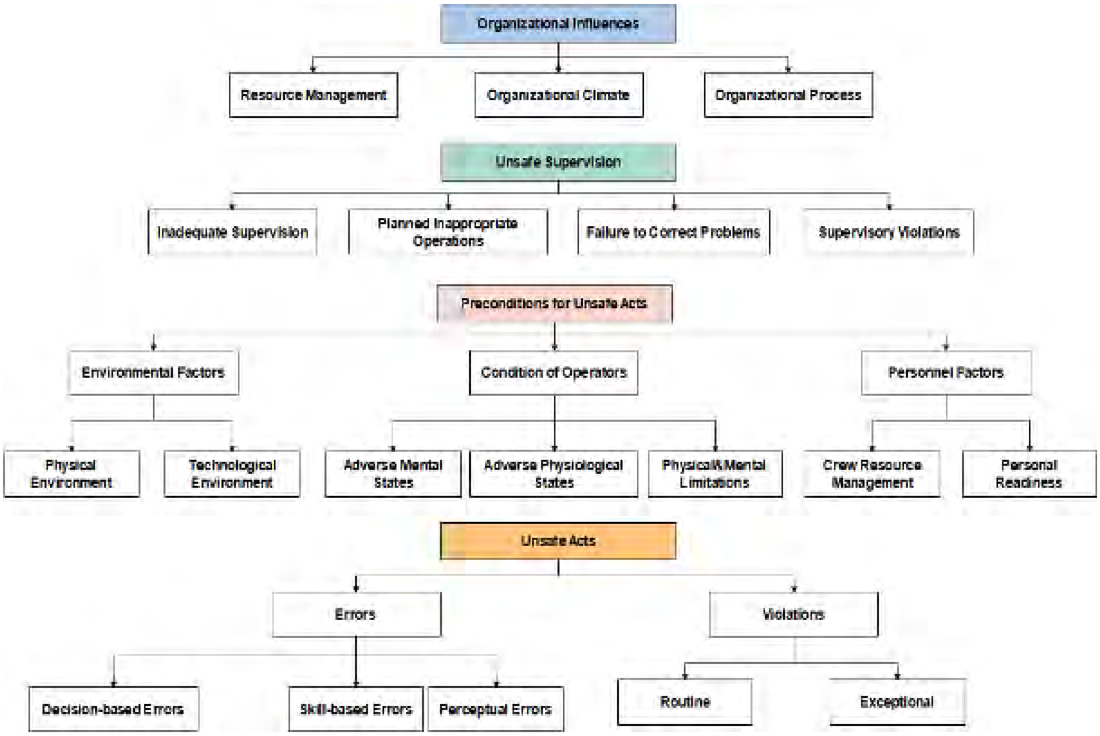


Figure 10. Traditional HFACS structure

The main structure of HFACS has been revised over time, taking into account the requirements of the accident type to which it is applied, and has been made compatible with the industry it is applied to. The first revision of the main HFACS structure was made by Shappell and Wiegmann [89]; they added environmental factors to HFACS. In many subsequent studies, environmental factors were examined under the pre-condition for the unsafe act framework with the sub-headings of the physical environment and technological environment. Tvaryanas et al. [91] classified the causes of accidents that occurred on aircraft used by German pilots under this new HFACS structure. They examined 221 accident reports published by German Federal Bureau of Aircraft Accident Investigation in their study. As a result of the study, the compatibility of the HFACS method with airway accidents was measured. In addition, the subjects that should be focused on in-flight training were determined, considering the most frequent mistakes made by pilots [91]. Theophilus et al. [92], in their study, introduced the customized HFACS-OGI (Human Factors Analysis and Classification System for the Oil and Gas Industry) model for oil and gas related accidents. In their study, they analysed 11 accident reports that occurred between 1998 and 2012 with the HFACS-OGI method. In the study, the accident causes associated with the oil and gas industry, which are difficult to categorize under the classical HFACS structure, have been successfully classified under the HFACS-OGI [86]. A HFACS-SIBCI (HFACS-Ship-Icebreaker Collision in Ice-covered waters) model was developed, which enables analysis of collision accidents that occur during icebreaker assistance in their studies. The accuracy of the developed HFACS-SIBCI model was proven through the analysis of 17 collision accidents [93]. Schröder-Hinrichs et al. [94] examined the ship engine room fire and explosion accidents with HFACS-MSS (HFACS-Machinery Spaces of Ships) method. In the study, 41 reports were examined and a total of 368 active factors failures were identified. The aim of the study was to reveal the effect of institutional organizational factors on ship engine room fires and to develop a specialized HFACS structure in order to analyse the human factor in engine room fires. As a result of the study, the latent factors were revised without changing the main HFACS structure, and a modified HFACS framework (HFACS-MSS) was introduced.

Environmental factors have been evaluated as latent factors (under the pre-conditions at for the unsafe act level) that play a role in the formation of root causes (unsafe act) in many accident studies related to the industry in aviation, railway, road transportation, oil, natural gas and mining [89, 95, 96, 97]. In maritime applications, this is also the case in many modified HFACS structures such as HFACS-MA (HFACS-Marine Accidents) [39], HFACS-ME (HFACS-Helicopter Maintenance Error) [98] and HFACS-MSS [35]. However, Uğurlu et al. [40] have revealed that environmental factors (operational conditions) are not a pre-condition that plays a role in the emergence of unsafe acts but are a complementary factor for unsafe actions to result in an accident. Therefore, they evaluated operational conditions on a separate level as the last level of HFACS. In this study, the modified HFACS (HFACS-PV) structure, outlined by Uğurlu et al. [75], is used for the accident analysis.

3.2 Scope and Methodology

In this part of the study, the compatibility of the HFACS-PV structure, that was put forward for the analysis of collision-contact accidents on passenger vessels [75], was tested for other accident types, and consists of 3 steps. In the first step, descriptive information was given about the content of the HFACS-PV structure. Thus, the HFACS-PV structure has become easily understandable. In step 2 of the study, the compatibility was tested for 3 different accident categories. These are contact, grounding and sinking. Unlike traditional HFACS structures, HFACS-PV contains 5 levels. When compared to other HFACS structures, the main change in the structure is the environmental factors (operational conditions). Environment is the 5th level of the structure (the last level) and it plays a role in turning unsafe act into an accident. The aim of the study in the second step is to try to explain why the environment should be examined at a last level unlike traditional HFACS structures by illustrative accidents. In the third step, 51 grounding accidents that occurred in passenger vessels between 1991 and 2017 were analysed under the HFACS-PV structure. The flow chart of the study has been presented in Figure 11. In this context, accident reports were obtained from 17 accident investigation institutions. In particular, Marine Accident Investigation Branch (MAIB), EMSA and Australian Transport Safety Bureau (ATSB), were examined.

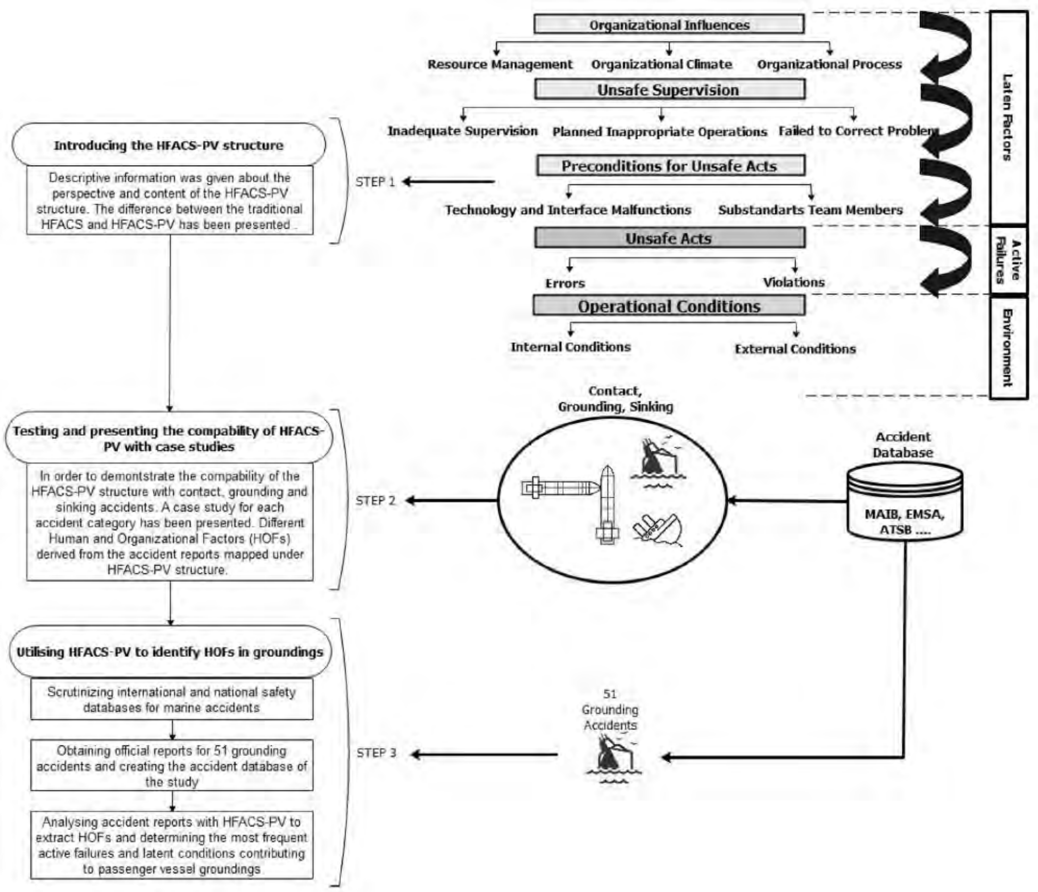


Figure 11. Flow chart of the study

The greatest issue with the extraction and mapping of the Human and Organizational Factors (HOFs), in the HFACS structure, is the varying opinions and thoughts of the different researchers as stated in Olsen's study [99]. A key reason for this is the different levels of the researchers' understanding of the HFACS structure. Improving and maintaining consistency regarding researchers' knowledge of both the individual HOFs and their specific definitions can greatly aid in solving and mitigating this problem. Within this study, the researchers are highly experienced and knowledgeable in both the HFACS structure and the definitions of its HOFs. In this HOF extraction and mapping process, the researchers individually coded and classified the HOFs, then the results were combined, and all coding was reviewed. It should be noted that all HOF codes were defined from accident reports. The process of discussing each individual HOF code was completed rigorously until a consensus was reached by all participants in the discussions. This methodology allows for considerable care to be taken to ensure that the codes are suitable and as accurate as possible. At this stage of the research 115 different HOFs were mapped under the HFACS-PV framework and thus the analysis of grounding accidents of passenger vessels is completed. Furthermore, in this research, no changes have been made to the HFACS-PV structure. The nonconformities under the HFACS-PV, which were identified by Uğurlu et al. [75], were supplemented by considering the causes of grounding accidents. In other words, new non-conformities (active failures and latent factors) associated with grounding accidents were added to the structure. Thus, the HFACS-PV structure is now compatible with grounding accidents. As a result of the study, the most important active failures, latent factors and operational conditions that have played a role in the occurrence of grounding accidents in passenger vessels, as well as proving the compatibility of the HFACS-PV structure with other accident types have been revealed.

3.3 HFACS-PV

Uğurlu et al. [75] used the classical HFACS method to analyse 70 collision-contact accidents that occurred on passenger vessels. However, they found that traditional HFACS structures are not suitable for the analysis of passenger vessel accidents. Therefore, they proposed a modified Human Factors Analysis and Classification System (HFACS-PV) structure for use in the analysis of the human factor in passenger collision-contact accidents (Figure 12). The HFACS-PV structure includes 5 main levels: Operational Conditions, Unsafe Acts, Pre-conditions for Unsafe Acts, Unsafe Supervision and Organizational Influences. Unlike conventional HFACS, the main change in the structure is the environmental factors (operational conditions) added to the structure. According to the HFACS-PV structure, each marine accident includes at least an operational condition. Operational conditions do not affect the decisions and actions of the operators (unsafe acts). On the contrary, it plays a complementary role in the transformation of unsafe action into an accident. Therefore, environmental factors in the modified HFACS-PV structure have not been examined under the pre-condition for unsafe act. The descriptive information about HFACS levels is given below.

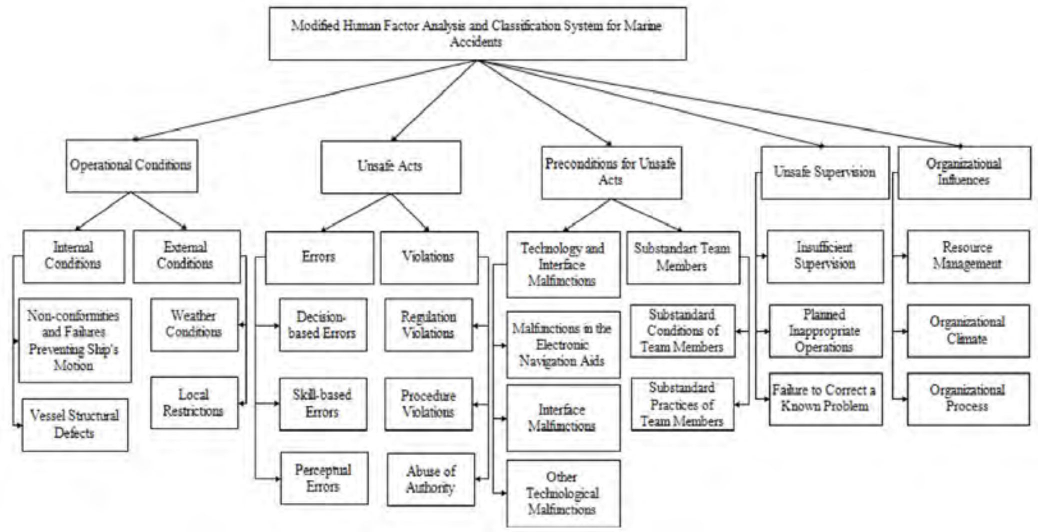


Figure 12. Modified HFACS-PV structure [40]

Operational Condition: It represents the last stage of the formation of a marine accident. Even if all the latent and active inconveniences required for the development of the accident come together, the accident will not occur unless the operational condition exists. For example, there is no possibility of a grounding accident unless the ship is navigating close to shallow waters. Operational conditions are divided into two categories: internal and external conditions. Internal conditions include vessel structural defects and non-conformities preventing ship motion. These are conditions that are partially controlled by operators. External conditions include non-ship factors that are not caused by human contribution or intervention. By using this classification, the effects of weather - sea conditions and local restrictions on marine accidents can be easily interpreted. The factors under the operational conditions are given in Figure 13.

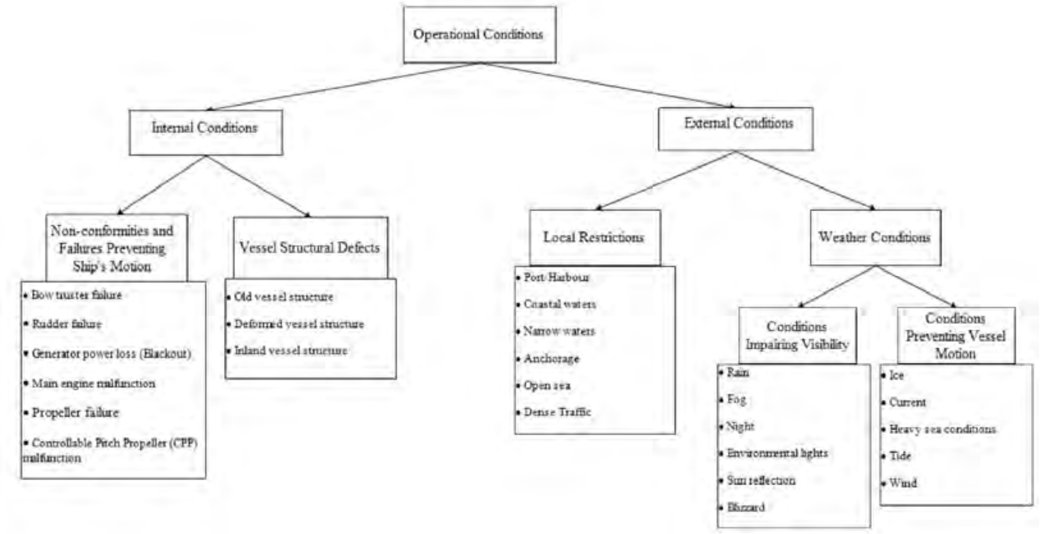


Figure 13. Operational conditions

Unsafe Act: Similar to the traditional HFACS structure, it is divided into 2 sub-categories: errors and violations made by ship crew on board [87]. Errors are unintentional actions [100] and consist of decision-based errors, skill-based errors, and perception errors. Skill-based errors are the errors made unconsciously due to lack of knowledge and experience. Decision errors are the result of choices and steps taken to reach a goal [101]. Perception errors are caused by visual, auditory, cognitive or attention problems. This usually happens in a restricted or impaired environment when sensory inputs are reduced. Violations are behaviours where rules and regulations are intentionally ignored [100]. Unlike the traditional HFACS structure, violations were divided into three sub-categories: rule violations, procedure violations, and abuse of authority [75]. Rule violations can be expressed as deliberate negligence or non-enforcement of legal regulations issued by the IMO, flag states or competent authorities. An example of procedure violations is the violation of berthing and anchoring procedures. Abuses are violations made deliberately by authorized persons. It can be described as the arbitrary use of the authority that is inconsistent with the safety practices or legal regulations. In Figure 14, the HOFs under the structure of unsafe acts are given.

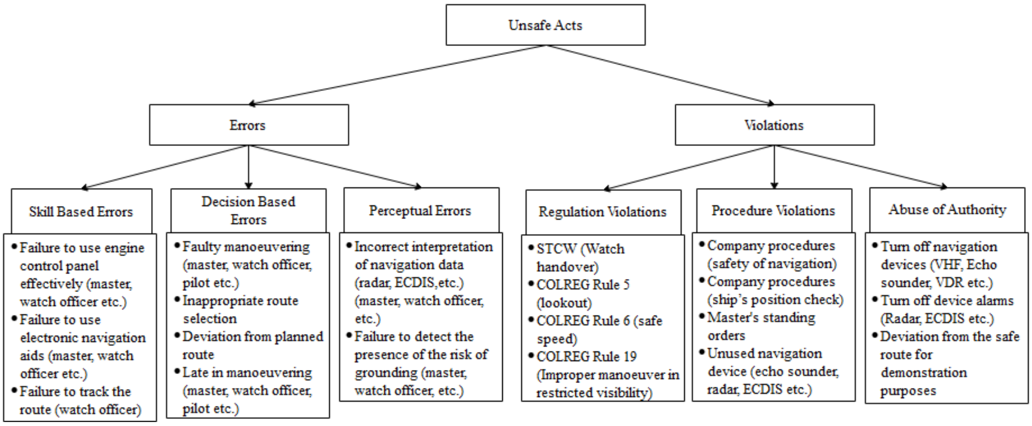


Figure 14. Unsafe Acts

Pre-Conditions for Unsafe Act: It has been emphasized by many researchers [89, 90], especially Shappell and Wiegmann [89] that this level is important in accident formation. Unlike other HFACS structures in the literature, this level is divided into two sub-categories: sub-standard team members, and technology and interface malfunctions to ensure compliance with marine accidents [39, 43, 44]. Technology and interface malfunctions pave the way for the formation of decision errors and perceptual errors. In other words, when a technological breakdown occurs, the decision and perception mechanism of the officer on the bridge is directly affected from it. For example, when a synchronization malfunction between Electronic Chart Display and Information System (ECDIS) and Global Positioning System (GPS) occurs, the ship's position may display as safe on the ECDIS screen, but it may actually be near risky shallow waters. In the presence of such a situation, an officer who sails with the ECDIS device may think that the ship is in safe waters and accordingly not notice the risk of grounding or contact. This increases the likelihood of an accident. In addition, due to the fact that ship management is carried out as a teamwork, "Operators" in the traditional structure are called "Team Members" in HFACS-PV. Figure 15 shows the non-conformities under this structure.

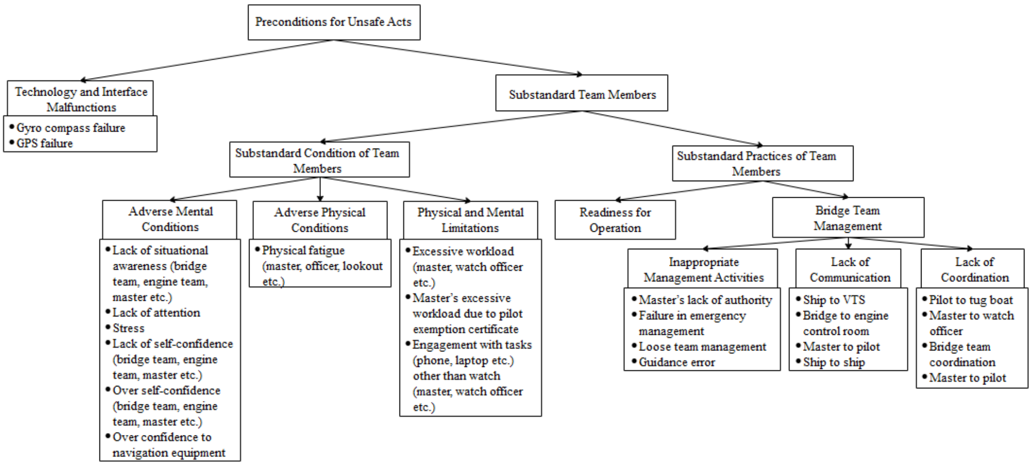


Figure 15. Pre-conditions for unsafe act

Unsafe Supervision: It has been examined under three sub-categories: insufficient supervision planned inappropriate operations and failure to correct the known problem. Non-conformities, such as deficiencies in tests and controls, delays in the operation of the planned maintenance system, planned inappropriate operations (e.g. voyage plan and the number of lookout in the shift), etc., are under the structure of unsafe supervision. In Figure 16, the HOFs under the unsafe supervision structure are given.

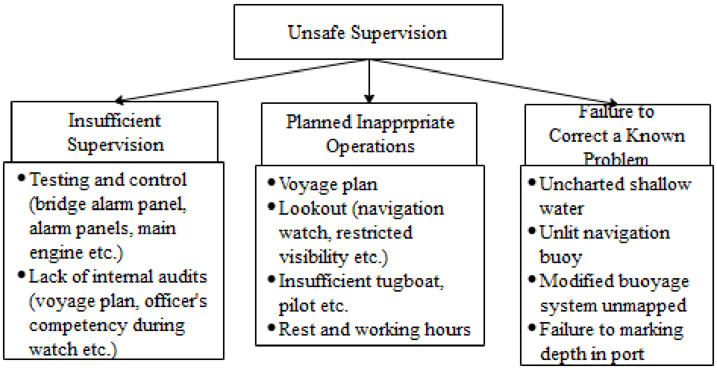


Figure 16. Unsafe supervision

Organizational Influences: As in other HFACS structures in the literature [89, 102, 103, 104], this level is divided into three sub-categories: resource management, organizational climate, and organizational process. Non-conformities related to the personnel and equipment resources, resource management strategies of companies, ship operators, and ports are placed under the Resource Management sub-category. HOFs affecting the performance of the seafarers, such as deficiencies and non-conformities related to the organizational structure, policies and corporate culture, are placed under the Organizational Climate sub-category [102, 105]. The deficiencies and non-conformities in the operational management, such as safety assessments (working/resting hours, time pressure, motivation, shift patterns) and reviews (risk analysis, risk management etc.) are included under the Organizational Process sub-category. The HOFs under organizational influences level are presented in Figure 17. Using the HFACS-PV structure described above, it is possible to examine the occurrence of ship accidents, to identify the active failures and latent factors affecting the accident as a chain of chain events.

3.4 Analysis of Accidents with HFACS-PV

In the previous sections, the number of HOFs under the HFACS-PV structure has been expanded and the compatibility of the structure with other accident types has been demonstrated by three chosen accidents. In this section, the active failures and latent factors of 51 grounding accidents occurring in passenger vessels are classified under HFACS-PV (Tables 12, 13, 14, 15 and 16). The name of the non-conformities detected for each level and their observation frequencies are also shown in Tables 12, 13, 14, 15 and 16. A total of 115 different HOFs were coded under the HFACS-PV structure, and they were observed 382 times in the accident reports (Tables 12-16). The pre-conditions for unsafe acts are the most significant with 25.1% (Table 14) for the occurrence of grounding accidents, followed by unsafe acts (23.3%) (Table 15), operational conditions (22.0%) (Table 16), organizational influences (20.4%) (Table 2) and unsafe supervision (9.2%) (Table 13). Similarly, studies of Xi et al. [104], Chen and Chou [102], Chen et al. [106] and Uğurlu et al. [75] identified and highlighted that pre-conditions for unsafe acts and unsafe acts are frequently observed in accidents. In many studies [94, 103, 106] based on the classical HFACS structure, environmental factors are considered under the pre-conditions for unsafe acts, which is one of the reasons why the pre-conditions for the unsafe acts level have a high degree of importance. When the studies of Celik and Cebi [107], Xi et al. [103], Chauvin et al. [87] and Chen et al. [106] are examined, it is seen that the importance ratio of environmental factors in accidents varies by 15-30%. This situation proves that environmental factors should be considered under a separate level from other levels for a more sensitive approach during the evaluation of HOFs.

When the first sub-categories underneath the main HFACS-PV levels are examined (Figure 18), Substandard Team Members (24.3%), External Conditions (20.7%), Errors (15.2%), Resource

Management (15.2%) and Unsafe Supervision (9.2%) appear to be the top five categories in the occurrence of grounding accidents on passenger vessels. The importance of the category Substandard Team Members, which is the most frequent first sub-category in the accidents examined, involving substandard conditions and practices of team members, has been highlighted in many studies [87, 89, 108]. In this context, the conclusion that the Substandard Team Members are an important human factor source in marine accidents is in line with the literature. Substandard Team Members include important nonconformities such as, lack of situational awareness, lack of attention, over-confidence, and fatigue. In order to eliminate or reduce marine accidents, these nonconformities should be focused on [94, 109]. As stated in studies of Chen et al. [106], Mazaheri et al. [110] and Graziano et al. [111] the second most important sub-category, weather conditions (wind, heavy seas, etc.) and local restrictions (coastal waters, narrow channel etc.) under the External Conditions level, must be taken into consideration in the operation planning.

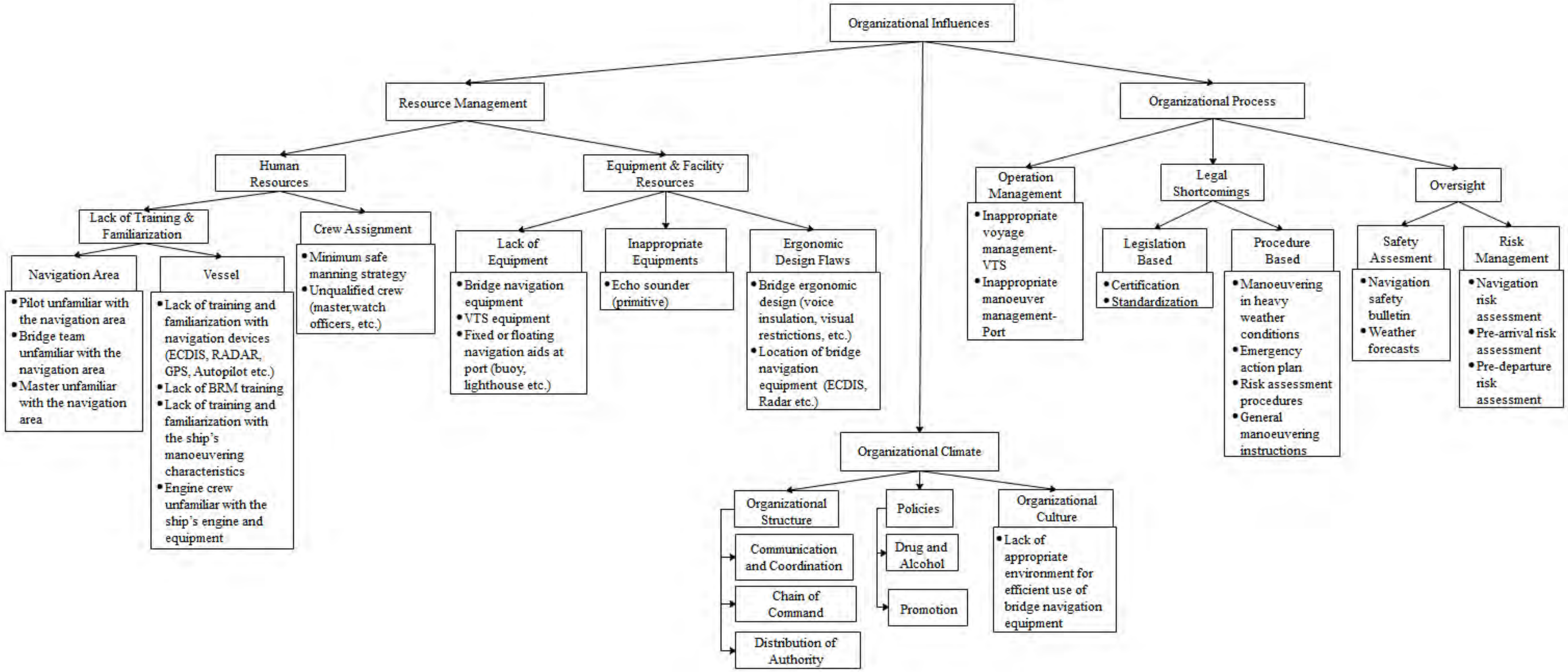


Figure 17. Organizational influences

When the HFACS-PV main levels were examined for grounding accidents, it can be seen that 78% of the accidents occurred due to human error [87, 88, 94, 107, 103, 109, 112, 113, 114, 115] Pre-conditions for unsafe acts (25.1%) and Unsafe acts (23.3%) are the most important levels that should be examined under human error in grounding accidents, followed by operational conditions (22%). The close proximity of the proportions of the levels revealed that environmental factors are at least as important as the other two levels in grounding accidents. Similarly, the effect of environmental conditions on marine accidents has been revealed in other studies in the literature [4, 89, 90, 109, 116, 117].

According to the findings of the study, violations have a share of 8.1% in grounding accidents. In order to prevent violations that play an important role in the occurrence of accidents, it is necessary to focus on the oversight (inspection) and control mechanism. The inspection and control mechanism should be operated effectively by the captain on board, the internal auditor at the company, and port and flag state officials in the countries. Another way to prevent violations is to provide a quality education and safety culture perception. The concept of safety culture is a cultural and social phenomenon that is difficult to acquire later. In order to prevent ship accidents, this phenomenon should be adopted not only individually but socially (ship-company). The study showed that the errors related to BRM are one of the effective pre-conditions (8.6%) in grounding accidents. HOFs such as deficient command chain on board, lack of communication and coordination, and lack of team spirit, are the main bridge team management errors. These non-conformities are the biggest obstacles to effective bridge team management on board, and this finding is also in line with the current literature [4, 24, 118, 119, 120, 121]. Good bridge team leadership of the master will make the team members adopt their tasks and their teammates and will make the ship operations safer. Therefore, when the ship operators are assigning a captain, they should consider avoiding early promotion, and assign the person who will take over the management of the entire ship based on their sea experience and passenger ship experience.

Table 12. Frequency of HOFs under Organizational Influence level

			f	%
Resource Management	Human Resources	**Lack of Training and Familiarization**		
		Vessel		
		Lack of training and familiarization with navigation devices (ECDIS, RADAR, GPS, Autopilot, *etc.*)	14	3.66
		Lack of BRM training	7	1.83
		Lack of training and familiarization with the ship's manoeuvring characteristics	4	1.05
		Lack of training and familiarization with the ship's propeller type	2	0.52
		Engine crew unfamiliar with the ship's engine and equipment	1	0.26
		Navigation Area		
		Pilot unfamiliar with the navigation area	1	0.26
		Bridge team unfamiliar with the navigation area	5	1.31
		Master unfamiliar with the navigation area	2	0.52
		Crew Assignment		
		Minimum safe manning strategy	4	1.05
		Inappropriate crew assignment (unqualified crew)	1	0.26
	Equipment & Facility Resources	**Lack of Equipment**		
		Bridge navigation equipment	5	1.31
		VTS equipment	1	0.26
		Fixed navigation aids at port	3	0.79
		Inappropriate Equipment and Facilities		
		Inappropriate echo sounder (primitive)	1	0.26
		Ergonomic Design Flaws		
		Inappropriate bridge design (voice insulation, visual restrictions, *etc.*)	6	1.57
		Arrangement of navigation equipment on bridge	1	0.26

Organizational Climate	Organizational Structure	**Communication and Coordination**	-	-
		Chain of Command	-	-
		Distribution of Authority	-	-
	Policies	**Promotion**	-	-
		Drug and Alcohol	-	-
	Organizational Culture	Appropriate environment for efficient use of bridge navigation equipment	1	0.26
Organizational Process	Operation Managemen	Inappropriate voyage management- VTS	2	0.52
		Inappropriate manoeuvre management- Port	2	0.52
	Legal Shortcomings	**Procedure Based**		
		Manoeuvring in heavy weather conditions	1	0.26
		Lack of emergency procedures	1	0.26
		Lack of risk assessment procedures	1	0.26
		Manoeuvring instructions	1	0.26
		Legislation Based		
		Navigation plan preparation	1	0.26
		Flag state’s manning standards	1	0.26
	Oversight	**Risk Assessment**		
		Ignoring risk assessment	4	1.05
		No pre-arrival checks	1	0.26
		Lack of check of navigation equipment before manoeuvre	1	0.26
		Safety Assessment		
		Failure to review the navigation safety bulletin	2	0.52
		Failure to check weather reports	1	0.26
		Total	78	20.4

Table 13. Frequency of HOFs under Unsafe Supervision level

		f	%
Insufficient Supervision	Bridge alarm panel	1	0.26
	Engine alarm panel	1	0.26
	Main engine routine overhaul	1	0.26
	Lack of internal audits	3	0.79
Planned Inappropriate Operations	Inappropriate navigation plan	13	3.40
	Watchkeeping without enough lookout	3	0.79
	Lack of tugboat to be used in manoeuvre	1	0.26
	Planning manoeuvre without tug	3	0.79
	Cargo shifting	1	0.26
	Navigating without pilot in icy waters	1	0.26
Failure to Correct a Known Problem	Existence of uncharted shallow water	5	1.31
	Modified buoyage system has not mapped	1	0.26
	Failure to mark port depths	1	0.26
	Total	35	9.2

Table 14. Frequency of HOFs under Pre-conditions for Unsafe Acts level

			f	%
Substandard Team Members	Substandard Conditions of Team Members	**Adverse Mental Conditions**		
		Lack of situational awareness (bridge team)	13	3.4
		Lack of situational awareness (master)	4	1.05
		Lack of situational awareness (engine team)	1	0.26
		Lack of attention	3	0.79
		Over self-confidence (bridge team)	2	0.52
		Over self-confidence (master)	5	1.31
		Over confidence in bridge navigation equipment	4	1.05
		Adverse Physical Conditions		
		Physical fatigue of the officer	2	0.52
		Physical and Mental Limitations		
		Excessive workload of watch officer	2	0.52
		Master's excessive workload due to pilot exemption certificate	2	0.52
		Lookout in night watch	20	5.24
		Excessive workload of master	1	0.26
		Master's occupation with phone	1	0.26
	Substandard Practices of Team Members	**Inappropriate Management Activities**		
		Master's lack of authority	2	0.52
		Failure in emergency management	5	1.31
		Master's lack of management	1	0.26
		Lack of briefing before navigation	1	0.26
		Lack of Communication		
		Lack of communication (Ship-VTS)	1	0.26
		Lack of communication (Bridge-Engine)	2	0.52
		Lack of communication (Master-Pilot)	4	1.05
		Lack of Coordination		
		Pilot-tug boat cannot agree on the intended manoeuvre	3	0.79
		Lack of coordination between master-watch officer	8	2.09
		Lack of bridge team coordination	3	0.79
		Master-pilot cannot agree on the intended manoeuvre	3	0.79
Technology and Interface Malfunctions		Gyro compass failure	1	0.26
		GPS failure	2	0.52
		Total	96	25.1

Table 15. Frequency of HOFs under Unsafe Acts level

			f	%
Errors	Skill Based	Master's inability to use engine control panel effectively	2	0.52
		Master's failure to detect the ship's heading by radar	1	0.26
		Failure of the watch officer to track the route	2	0.52
		Failure of bridge team to use ECDIS	2	0.52
		Failure of the watch officer to use the variable range marker	1	0.26
		Failure of the watch officer to use navigation devices	4	1.05
		Master's failure to use the ship's propellers in synchronized mode	2	0.52
		Watch officer's failure to use rudder modes (follow up, non-follow up *etc.*)	1	0.26
		Failure of bridge team to use autopilot in port mode	2	0.52
		Master's failure to use navigation equipment	6	1.57
		Incorrect tide calculation of bridge team	1	0.26
		Inability of the bridge team to apply parallel index on radar	2	0.52
	Decision Based	Watch officer's manoeuvring error	1	0.26
		Bridge team member's manoeuvring error	3	0.79

		Master makes turn by using autopilot in the narrow waterway	2	0.52
		Master's faulty manoeuvre to avoid collision	1	0.26
		Improper route selection	4	1.05
		Deviation from planned route	4	1.05
		Master's disregard of pilot advices	1	0.26
	Perceptual	Interpretation error of bridge team	2	0.52
		Master's interpretation error	9	2.36
		Master's failure in detection of the existing danger (COLREG Rule 8)	5	1.31
Violations	Regulation	Watch handover (STCW)	1	0.26
		Improper lookout (COLREG Rule 5)	1	0.26
		Unsafe speed (COLREG Rule 6)	6	1.57
		Improper manoeuvre in restricted visibility (COLREG Rule 19)	1	0.26
	Procedure	Safety of navigation	4	1.05
		Vessel position check	4	1.05
		Inappropriate chart usage	2	0.52
		Inability to use echo sounder in restricted waters	3	0.79
	Abuse of Authority	Deleting VDR records (destroying evidence)	6	1.57
		Deviation from the safe route for demonstration purposes	3	0.79
		Total	89	23.3

Table 16. Frequency of factors under Operational Conditions level

			f	%
External Conditions	Weather Conditions	**Impairing Visibility**		
		Fog	1	0.26
		Preventing Vessel's Motion		
		Heavy seas	1	0.26
		Ice condition	4	1.05
		Tide	5	1.31
		Current	7	1.83
		Strong wind	8	2.09
	Locational Restrictions	Port	26	6.81
		Narrow water	19	4.97
		Coastal water	6	1.57
		Heavy traffic	2	0.52
		Open sea	-	-
Internal Conditions	Non-conformities and failures of preventing the ship's motion	Engine failure	2	0.52
		Rudder failure	2	0.52
		Generator power loss (Blackout)	1	0.26
	Vessel Structural Defects		-	-
		Total	84	22.0

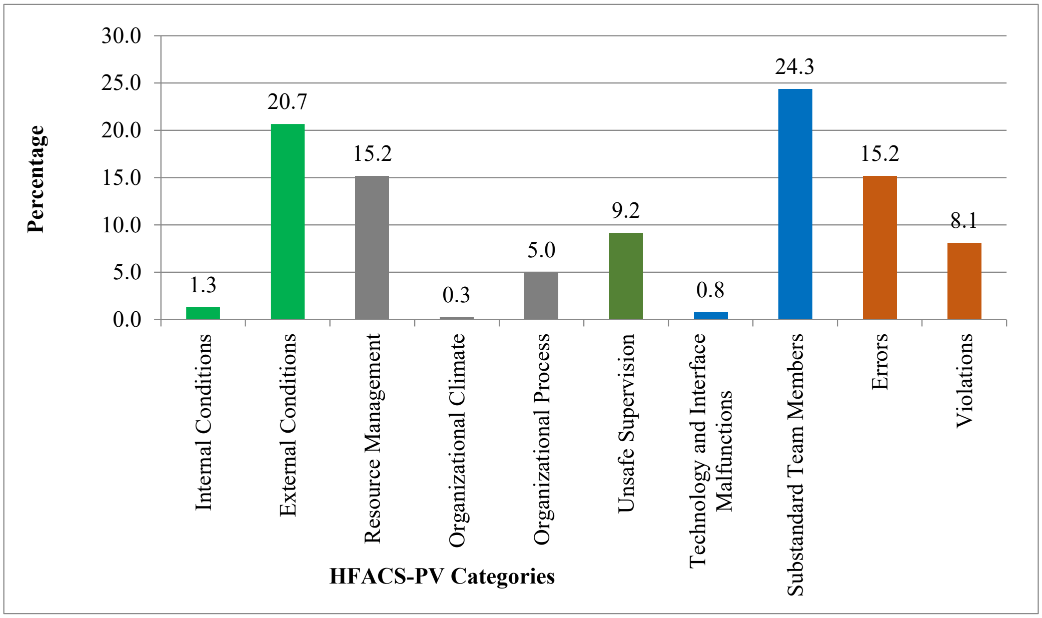


Figure 18. Percentage distribution of HFACS-PV sub-categories in grounding accidents

3.5 Analysis of Dover Strait Accidents using HFACS-PV

The HFACS-PV framework outlined in Figure 12 was applied to 17 grounding accidents and 10 collision/contact accidents in the Dover Strait. These accidents occurred between 2004 and 2020. Sinking accidents have not been analysed in this study as there was only 1 sinking accident in the Dover Strait in this period. The information regarding the grounding and collision accidents was obtained from accident reports. These accident reports were sourced from a number of accident databases, such as the Global Integrated Shipping Information System (GISIS) and Marine Accident Investigation Branch (MAIB). Each accident report was meticulously scrutinised to determine the causes of the marine accidents using the HFACS-PV approach.

3.5.1 Grounding Accidents

17 grounding accidents were analysed using the HFACS-PV structure. in order to achieve this, the accident reports for each accident were carefully and coherently examined to apply the methodology to the accident. This allowed for root causes, in terms of human error to be identified. Furthermore, these results were collated to highlight the most significant categories in the HFACS-PV structure. Figure 19 demonstrates the occurrence, by percentage per accident, of preconditions for grounding accidents.

It can be seen in Figure 19 that Unsafe Acts: Errors were observed in 28.6% of grounding accidents in the Dover Strait. This is followed by Substandard Team Members (19%), under Preconditions for Unsafe Acts. When the Errors category is examined, it can be seen that 68.8% of the errors that occurred were Decision Based Errors, followed by 62.5% for Perceptual Errors and 18.8% for Skill-Based errors. This shows that errors resulting from the skill level of the crew do not majorly contribute to grounding accident causes. However, it is clear that the perceptions and decisions made by the bridge team result in a grounding accident in more than 2/3 of grounding accidents.

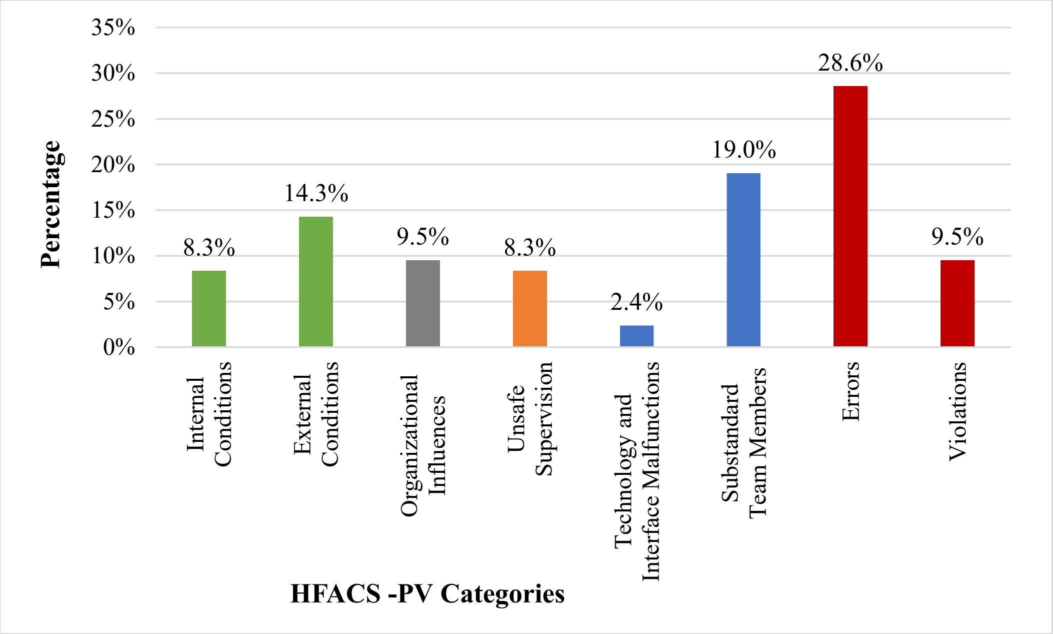


Figure 19. Occurrence per accident of preconditions for grounding accidents in the Dover Strait

This is reinforced by the analysis of Preconditions for Unsafe Acts: Substandard Team Members (19%), where Substandard Condition of the Team Members is highlighted as a cause in 31.3% of grounding accidents in the Dover Strait, but Substandard Practices of Team Members occurs in 68.8%.

The top 3 causes of grounding accidents are thus found to be:

- Substandard Practices of Team Members – 68.8%
- Decision Based Errors – 68.8%
- Perceptual Errors – 62.5%

All of these accident causes are linked to the practices and the conduct of the bridge team in the preconditions for a grounding accident. Similarly, following the 3 preconditions listed above, the next highest cause for grounding accident was External Conditions: Weather Conditions with an occurrence of 56.3% of grounding accidents. In terms of Unsafe Acts: Errors, there is concurrence with the literature examined in Section 1.1.1, where fatigue, distractions and external influence are 3 of the main causes of grounding, sinking or collision/contact accidents. Similarly, when looking at Substandard Practices of Team Members, the literature also highlights Teammate Influence and Task Deviation as root causes of these marine accidents. Table 17 outlines the compete distribution of HFACS-PV Categories and Sub-Categories for grounding accidents in the Dover Strait

Table 17. Percentage distribution of HFACS-PV Categories and Sub-Categories for grounding accidents in the Dover Strait

			Total	f/acc.	f/acc. (%)	tot/category	% dis. Per category
Operational Conditions	Internal Conditions	Non-Conformities and Failures to Prevent Ship Motion	6	0.38	37.5%	7	8.3%
		Vessel Structural Defects	1	0.06	6.3%		
	External Conditions	Weather Conditions	9	0.56	56.3%	12	14.3%
		Local Restrictions	3	0.19	18.8%		
	Organizational Influences	Resource Management	2	0.13	12.5%	8	9.5%
		Organisational Climate	2	0.13	12.5%		
		Organisational Processes	4	0.25	25.0%		
	Unsafe Supervision	Insufficient Supervision	1	0.06	6.3%	7	8.3%
		Planned Inappropriate Operations	1	0.06	6.3%		
		Failure to Correct a Known Problem	5	0.31	31.3%		
Preconditions for Unsafe Acts	Technology and Interface Malfunctions	Malfunction in the Electronic Nav Aids	1	0.06	6.3%	2	2.4%
		Interface Malfunction	0	0.00	0.0%		
		Other Tech. Malfunctions	1	0.06	6.3%		
	Substandard Team Members	Conditions of Team Members	5	0.31	31.3%	16	19.0%
		Practices of Team Members	11	0.69	68.8%		
Unsafe Acts	Errors	Decision Based Errors	11	0.69	68.8%	24	28.6%
		Skill Based Errors	3	0.19	18.8%		
		Perceptual Errors	10	0.63	62.5%		
	Violations	Regulation Violations	1	0.06	6.3%	8	9.5%
		Procedure Violations	4	0.25	25.0%		
		Abuse of Authority	3	0.19	18.8%		
						84	100.0%

3.5.2 Collision/Contact Accidents

Collision/contact accidents were analysed in the same manner as the grounding accidents in Section 3.5.1. Figure 20 demonstrates the occurrence, by percentage per accident, of preconditions for collision/contact accidents.

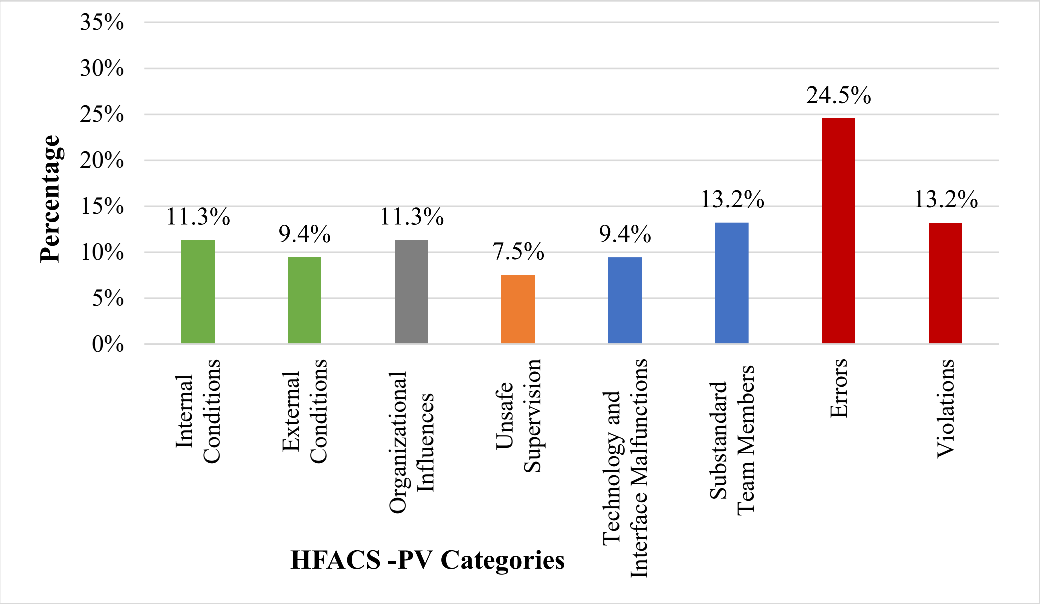


Figure 20. Occurrence per accident of preconditions for collision/contact accidents in the Dover Strait

It can be seen in Figure 20 that Unsafe Acts: Errors (24.5%) again occur the most in terms of accident preconditions and causes, as with grounding accidents. However, the next most influential preconditions are; Substandard Team Members and Violations, both 13.2% occurrence respectively. These categories can be further examined to a more finite level by looking at the most influential sub-categories, as follows:

- Unsafe Acts: Errors (24.8%)
    - Decision Based Errors (37.5%)
    - Perceptual Errors (25%)
    - Skill-Based Errors (18.8%)
- Substandard Team Members (13.2%)
    - Conditions of Team Members (25%)
    - Practices of Team Members (18.8%)
- Violations (13.2%)
    - Procedure (18.8%)
    - Regulation (12.2%)
    - Abuse of Authority (12.5%)

As with grounding accidents it is the perceptions and decision making of the bridge crew that have led to collision/contact accidents. Similarly, the increase occurrence of violations, particularly procedural violations is in concurrence with collision accidents as the bridge crew must be able to identify a vessel in close proximity, decide on avoidance and carry out the correct procedure to ensure collision avoidance. All of these failures in multiple combinations are proven to result in collision accidents. Furthermore, what should be noted is that despite the other categories being consistent but low, there are a number of preconditions which exist that also play a role in collision/contact accidents. The most influential of these are outlined as follows, along with their percentage occurrence per collision/contact accident:

- Internal Conditions (11.3%)
    - Non-Conformities and Failures to Prevent Ship Motion (31.3%)
- External Conditions (9.4%)
    - Weather Conditions (18.8%)
- Organizational Influences (11.3%)
    - Organisational Processes (18.8%)
- Technology and Interface Malfunctions (9.45)
    - Other Tech. Malfunctions (18.8%)

It can be seen that collision/contact accidents are more complicated in their accident formation. It has been found in this research and in other literature studies [74, 75] that a combination of events preconditions is required for a collision/contact to occur. One example is a combination of harsh weather conditions and technological problems (such as electronic navigation failure), or lack of awareness from the watch team and failure to follow procedure/incorrect company procedure. Table 18 outlines the compete distribution of HFACS-PV Categories and Sub-Categories for collision/contact accidents in the Dover Strait

Table 18. Percentage distribution of HFACS-PV Categories and Sub-Categories for collision/contact accidents in the Dover Strait

			Total	f/acc.	f/acc. (%)	total/ category	% dis. Per category
Operational Conditions	Internal Conditions	Non-Conformities and Failures to Prevent Ship Motion	5	0.31	31.3%	6	11.3%
		Vessel Structural Defects	1	0.06	6.3%		
	External Conditions	Weather Conditions	3	0.19	18.8%	5	9.4%
		Local Restrictions	2	0.13	12.5%		
	Organizational Influences	Resource Management	1	0.06	6.3%	6	11.3%
		Organisational Climate	2	0.13	12.5%		
		Organisational Processes	3	0.19	18.8%		
	Unsafe Supervision	Insufficient Supervision	1	0.06	6.3%	4	7.5%
		Planned Inappropriate Operations	1	0.06	6.3%		
		Failure to Correct a Known Problem	2	0.13	12.5%		
Preconditions for Unsafe Acts	Technology and Interface Malfunctions	Malfunction in the Electronic Nav Aids	1	0.06	6.3%	5	9.4%

		Interface Malfunction	1	0.06	6.3%		
		Other Tech. Malfunctions	3	0.19	18.8%		
	Substandard Team Members	Conditions of Team Members	4	0.25	25.0%	7	13.2%
		Practices of Team Members	3	0.19	18.8%		
Unsafe Acts	Errors	Decision Based Errors	6	0.38	37.5%	13	24.5%
		Skill Based Errors	3	0.19	18.8%		
		Perceptual Errors	4	0.25	25.0%		
	Violations	Regulation Violations	2	0.13	12.5%	7	13.2%
		Procedure Violations	3	0.19	18.8%		
		Abuse of Authority	2	0.13	12.5%		
						53	100%

4 Dynamic Risk Modelling

It has been stated in literature that dynamic risk modelling can have a great impact on safety and risk analysis in marine and maritime operations. Khakzad, et al., (2013) [122] proposed to apply BN to Bow-Tie (BT) analysis. They postulated that the addition of BN to BT would help to overcome the static limitations of BT and show that the combination could be a substantial dynamic risk assessment tool. Similarly, in the oil, gas & process industry (Yang & Mannan, 2010) [123] proposed a methodology of Dynamic Operational Risk Assessment (DORA). This starts from a conceptual framework design to mathematical modelling and to decision making based on cost-benefit analysis. Furthermore, Eleye-Datubo, et al. (2006) [124] proposes an offshore decision-support solution, through BN techniques, to demonstrate that it is necessary to model the assessment domain such that the probabilistic measure of each event becomes more reliable in light of new evidence being received. As opposed to obtaining data incrementally, causing uncertainty from imperfect understanding and incomplete knowledge of the domain being analysed.

Furthermore, dynamic risk assessment has been developed through the use of BT alone. Abimdola et al., (2014) [125] present a dynamic risk assessment model utilising the BT approach. The work outlines a predictive failure probabilistic model which is determining failure probabilities of basic components of during drilling operations. The dynamic model is capable of updating the failure probabilities of the components of the bowtie, thus, overcoming the static nature of common risk assessment techniques [125] Other research has developed algorithms tailored to specific incidents and events. For example, Liu et al., (2016) [126] developed a system specific, novel methodology coupling the reservoir/wellbore model with distribution of uncertainties of a number of independent variables to obtain a risk picture of possible uncontrolled wellbore flow events. They state that industry could implement this methodology with minor modification as a benchmark to evaluate the onshore/offshore blowout risk [126]

4.1 Bayesian Networks in Dynamic Risk Assessment

The risk of hazards and failures offshore is determined by a huge array of factors due to the innumerable possible scenarios in which incidents and accidents can develop. This makes establishing risk both qualitatively and quantitatively an intimidating task. There are many techniques which can aid risk analysis, yet in this report the focus is to be around BNs, and a large number of studies have been conducted for the marine industry. Most studies usually associate themselves around a particular area. For example, BNs have been utilised by Cai, et al., (2013) [126] to conduct quantitative risk assessment of operations in the offshore oil and gas industry. Their method involves translating a flow chart of operations into the BN directly. They then validate their model through the use of a case study involving Subsea Blowout Preventer Operations, in light of the Deepwater Horizon sinking in 2010, whose cause was the failure of subsea blowout preventer [128]. In another instance, Eleye-Datubo, et al. (2006) [124] apply BN to produce a marine decision support tool to realistically deal with random uncertainties, while at the same time making risk assessments easier to build and to check (Fenton & Neil, 2013). Continually, Wu et al. (2016) further apply the use of Bayesian Networks for prediction and diagnosis of marine systems given certain conditions. Their work also applies the use of the BT approach to develop the BN and apply a case study (Wu, et al., 2016) [129]. This application of merging the BT approach with the BN approach is not uncommon which can be clearly seen in the outlined literature. Furthermore Loughney & Wang (2017) [130] and Loughney et al. (2018) [131] have utilised BNs to demonstrate that BNs can provide an effective and applicable method of determining the likelihood of various events under uncertainty. The model can be used to investigate various scenarios around the systems and components outlined and to show the beginnings of establishing where attention should be focused within the objective of preventing offshore incidents, as well as having a clear representation of specifically where these accidents can originate from.

There are several advantages of using BNs over alternate approaches, for example, in BNs diverse data, expert judgement and empirical data can all be combined. This is very useful in situations where there is incomplete data or a complete absence of data, and thus other forms of data and information can be incorporated into the network [132]. The advantageous nature of BNs over other methods is outlined by Khakzad, et al., (2011) [122], who presented a journal paper with the exclusive nature of comparing BNs and Fault Tree Analysis (FTA) in safety analysis within the process industry. It was concluded by Khakzad, et al., (2011) [122] that a BN is a superior technique in safety analysis due to its flexible structure, which allows for it to fit a wide variety of accident scenarios. These views are also supported by Wu et al. (2016) [129] and Yeo et al., (2016) [133].

In conjunction to this, BNs provide a clear visual depiction of what they are representing and can be a very powerful tool for formulating ideas and expanding the model in itself [134]. This trait is shared by other risk modelling techniques; however, BNs are particularly adaptable method. BNs also facilitate inference and the ability to update predictions through the insertion of new evidence or observations into its parameters. This makes them a very useful tool when dealing with uncertainty.

4.2 Formation of BN Developed from Main HFACS-PV Structure

This study is an accident analysis that examines marine accidents that have occurred in the Istanbul Strait and the Dover Strait, between 2004 and 2020. In this context, a total of 274 (IS:240, DS:34) out of 6,548 marine accidents were taken as the data set to be used in the study. In all of these accidents, at least one of the ships involved is subject to IMO regulations (vessels of 500 gross tonnage and above). In this study, grounding, sinking, collision-contact accidents were investigated for the Istanbul Strait and only grounding and collision /contact were analysed for the Dover Strait as there was only 1 sinking accident in this area in this time frame.

4.2.1 Gathering the accident data and choosing the appropriate method for accident analysis

The dataset of this study considers all accident recorded between 2004 and 2020 in the specified regions. A very serious marine casualty involves the total loss of the ship or a death or severe damage to the environment [134]. 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 [135].

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), Marine Accident Investigation Branch (UK) 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 IS and DS by considering accident reports, accident analysis studies, and qualitative and analytical models used in accident analysis. In order to analyse accident reasons, HFACS (qualitative) and BN (both qualitative and quantitative) methods, which are widely used in many accidents analysis studies, have been chosen.

4.2.2 Overview of Bayesian theory and 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 [136, 137, 138, 139]. 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 [130, 131, 140, 141].

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' [124, 139, 141, 142]. Conditional probabilities are part of the joint probability of the intersection of A and B, $P(A \cap B)$, and can be shown as:

$$P(A \mid B) = P(A \cap B)/P(A) \tag{2}$$

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) [139]. Determining the probabilities of parent nodes, root nodes and child nodes is very important for the results of the study [139].

4.2.3 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 frameworks created in Section 4. 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 as well as expert judgement for nodes where data is not available. Once the relevant nodes and CPTs are identified, they are input into a BN software package, GeNIe Academic. The network is reviewed to ensure that there are no missing factors. The main structure and sub-elements of the HFACS structure that has been formed for this study, for the accidents that fall under grounding sinking and collision/contact are presented in Figure 21. The BNs which have been constructed on the basis of the main HFACS structure are shown in Figure 22 and 23 for the IS and DS respectively.

4.3 Application of the BN Model: Case study for Istanbul Strait.

The BN model for the Istanbul strait was tested based on a grounding accident while at anchorage. The information known prior to the accidents was inserted into the BN models and the consequence probabilities were evaluated. Similarly, the information that became known during the accident, that should have been known and/or shared before the accident was also inserted into the model to evaluate the potential change in consequence probability. This allows for the validity of the BN model to be evaluated based on real time scenarios and accidents.

4.4 Grounding accident in Istanbul Strait: British Enterprise

4.4.1 Brief Narrative

On 11 December 2004, at about 1405, the UK registered tanker British Enterprise grounded in the Port of Istanbul, Ahirkapi Anchorage Area (Kadikoy VTS Sector – see Figures 4 and 5). The vessel was aground for 5 days before she was floated off following a lightening operation. There was no damage to the vessel and no pollution. The vessel passed southbound through the Istanbul Bogazi during the morning of 11 December. The master then advised the VTS he wished to take bunkers and requested an anchor position. Permission was granted and he was instructed to anchor in “Charlie flammable cargo and explosives anchorage”. The master anchored the vessel in section C6 of the anchorage later that morning at 05:46.

Once bunkering was completed, and the barges were gone and clear, the master informed the VTS he was ready to depart and was duly granted permission to sail from the port. The anchor was weighed at 13:43, the master turned the vessel around using rudder and engine, and began proceeding out of C6 anchorage, intending to cross C5 anchorage before heading out to sea. She had a maximum draught of 11.17 metres.

At 1405, as British Enterprise passed through C5 anchorage, the master noticed the vessel’s speed had reduced to zero and, realising she was aground, he immediately stopped her engine. The bridge team checked the position and, after confirming that the chart showed sufficient water depth for the vessel (between 13 and 14 metres), the master attempted to manoeuvre her clear of what appeared to be an

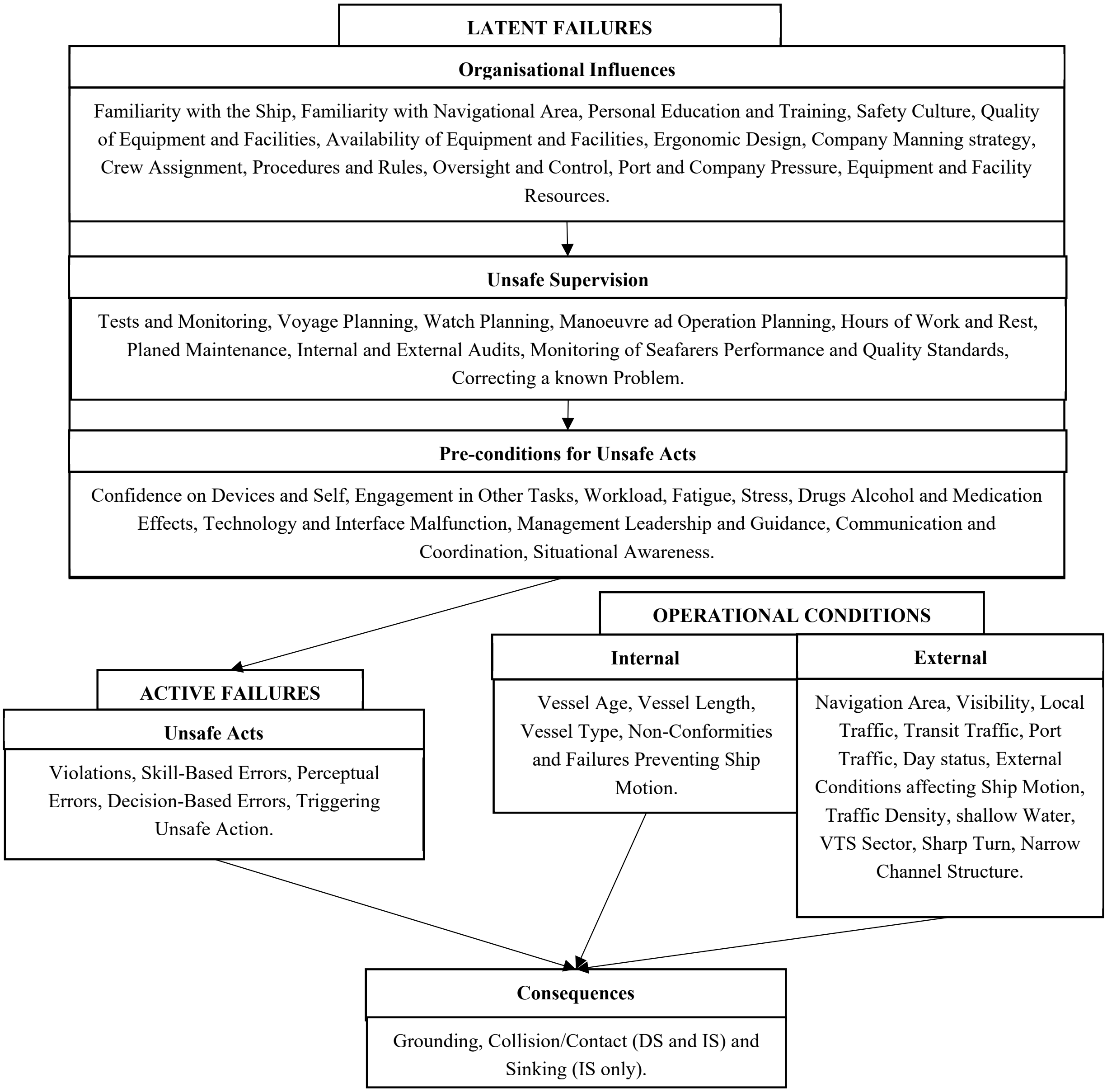


Figure 21. Main structure and sub-elements of HFACS developed for this study

uncharted shoal or obstruction. At 1440, the master realised the vessel was hard aground, and he advised the VTS of the situation.

Given the information presented in the accident report on the investigation of the grounding of British Enterprise [143], the BN for the Istanbul Strait (see Figure 22) was updated to reflect the known information. In this case the evidence inserted into the BN model is what the master of the vessel knew at the time while in anchorage in area C6. Table 19 demonstrates the nodes in the BN where evidence has been altered, as well as the specific state of the node that has been updated, the prior occurrence based on all accidents, and the new evidence value based on the *British Enterprise* Operational Conditions and Organisational Influences.

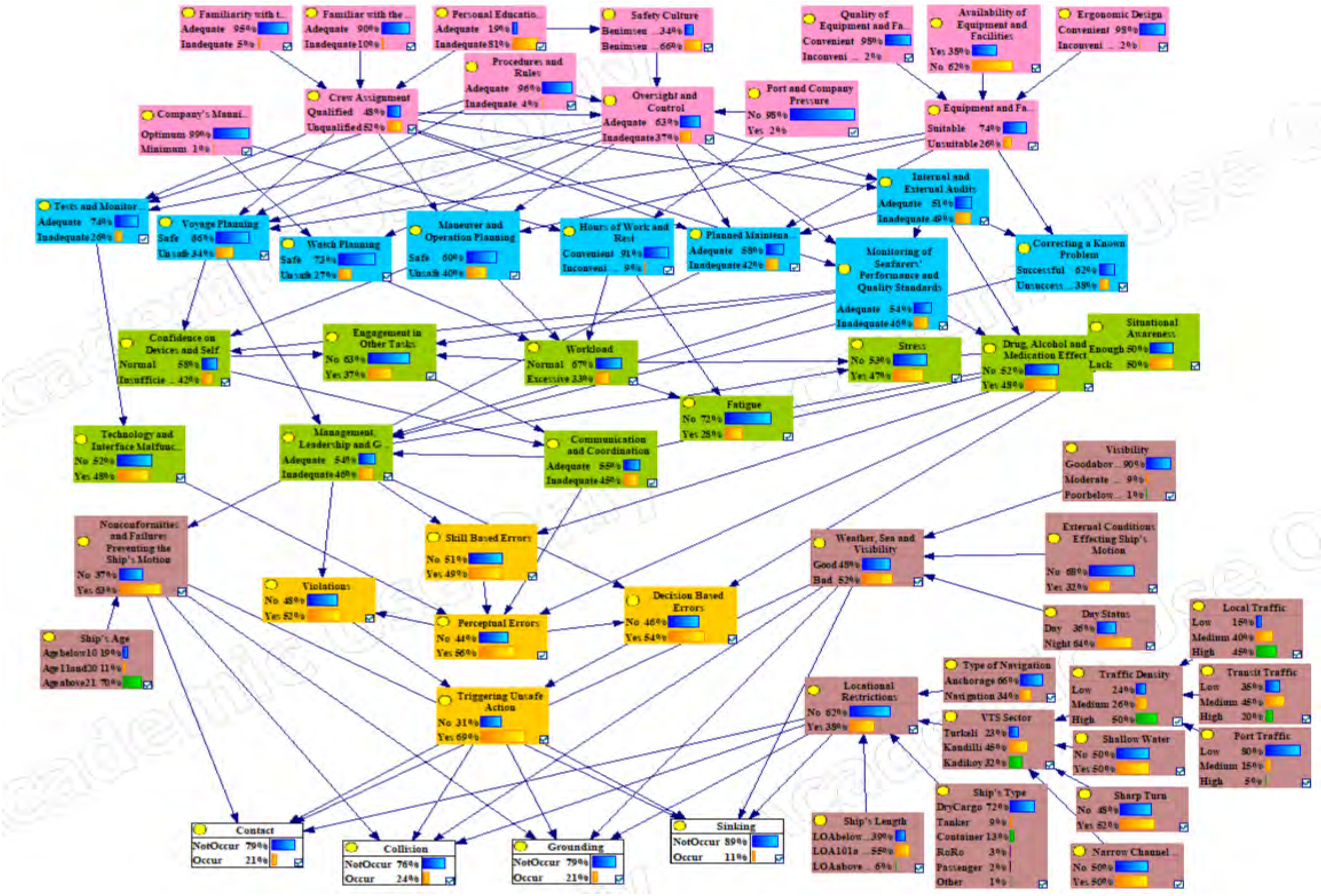


Figure 22. BN model for collision-contact, grounding and sinking occurring in the Istanbul Strait

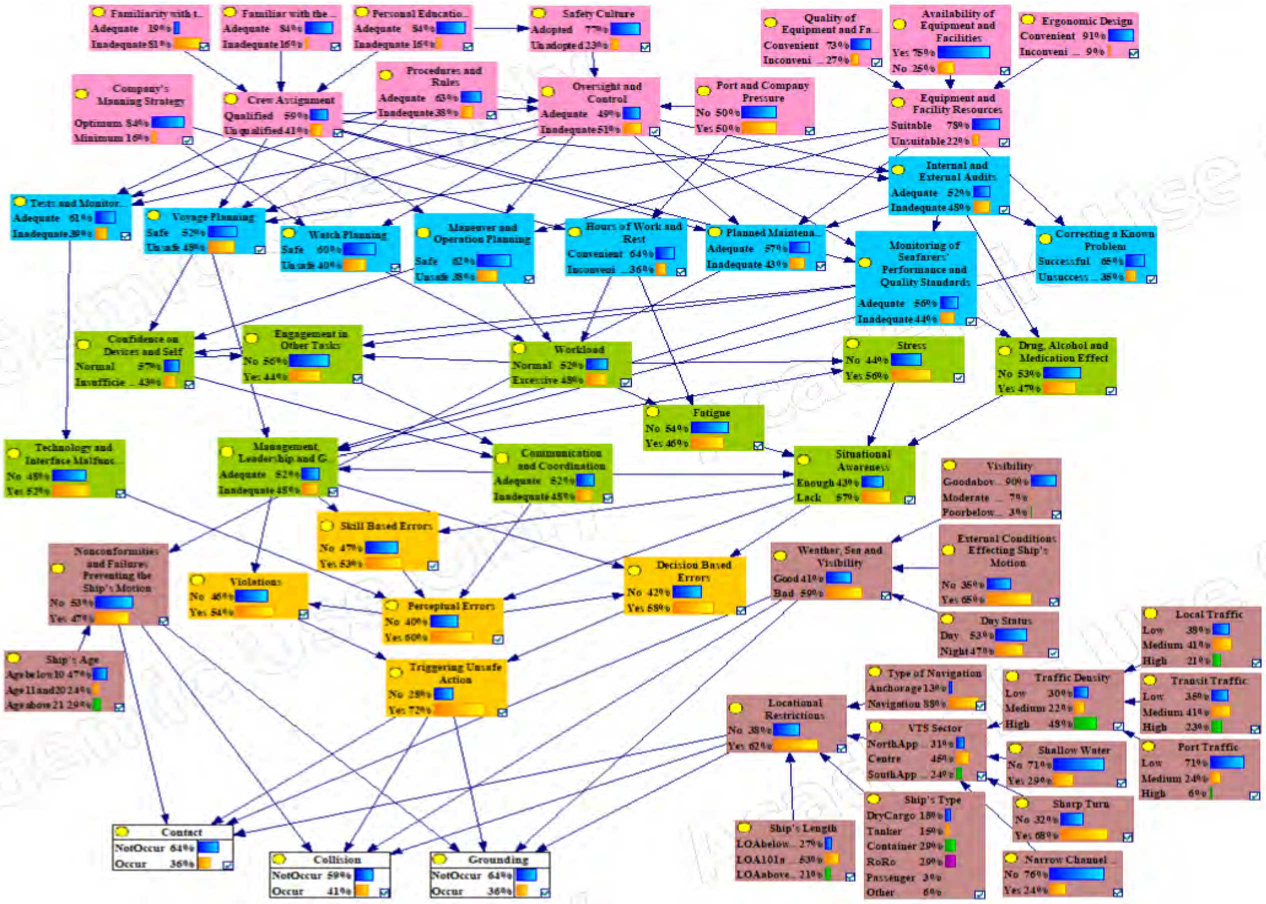


Figure 23. BN model for collision-contact, grounding and sinking occurring in the Dover Strait.

4.4.2 BN Analysis: Grounding

It can be seen that the consequences of contact, collision and grounding all decrease by 10%, 9% and 10% respectively. Thus, it can be assumed that the information that the crew of the *British Enterprise* had was sufficient enough that a grounding was unlikely to occur. The reason that the chance of a collision is higher than a grounding or contact is that there were multiple vessels in the area, in a somewhat tight formation. Hence the insertion of evidence in the node "Local Traffic – Medium". Figure 24 is based on information in the accident report and shows the anchorage orientation when the *British enterprise* was stationary. Figure 24 was developed for testing in the Bridge Simulator, which is discussed in Section 6.

Table 19. Updated nodes and states in the BN model relating to known information by the crew of the British Enterprise.

Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with Ship	Adequate	95%	100%	5%
Familiarity with Navigational Area	Adequate	90%	100%	10%
Personnel Education and Training	Adequate	19%	100%	81%
Quality of Equipment and Facilities	Convenient	98%	100%	2%
Availability of Equipment and Facilities	Yes	38%	100%	62%
Ergonomic Design	Convenient	98%	100%	2%
Company's Manning Strategy	Optimum	9%	100%	91%
Port and Company Pressure	No	98%	100%	2%
Operational Conditions - Cause				
Navigational Area	Anchorage	66%	100%	34%
VTS Sector	Kadikoy	32%	100%	68%
Ship type	Tanker	9%	100%	91%
Ship Length	LOA101-200m	39%	100%	61%
Ship age	Below10years	19%	100%	81%
Visibility	Good above5nm	90%	100%	10%
External Conditions Affecting Ship Motion	Yes	32%	100%	68%
Local Traffic	Medium	40%	100%	60%
Transit Traffic	Low	35%	100%	65%
Port Traffic	Low	80%	100%	20%
Sharp turn	Yes	52%	100%	48%
Narrow Channel	No	50%	100%	50%
Shallow Water	No	52%	100%	48%
Consequence - Effect				
Contact	Occur	33%	23%	-10%
Collision	Occur	37%	28%	-9%
Grounding	Occur	33%	23%	-10%

Based on the known information, the vessel should not run aground, however, there was a piece of information not known to the crew of the *British Enterprise* but was known to the local port authority. Adjacent to the left of anchorage C6 is anchorage C5, as shown in Figure 24. In the 3 years prior to the grounding of the *British Enterprise* 2 other vessels had also run aground in anchorage C5. The Turkish flag bulk carrier Henza, on a voyage from the Black Sea to China, laden with 63,478 metric tonnes of fertiliser, grounded in C5 anchorage on 17 February 2003. An investigation into the grounding was completed by the port authority. The investigation concluded that, as the vessel had a maximum draught of 13.05 metres, and she grounded in an area with a charted depth of between 13 and 14 metres, the principal causal factors were the actions of the master and his navigating team. The investigation did not uncover any discrepancy between the actual and charted depths; therefore, no re-survey of the area was made. The vessel was aground for more than 3 weeks while the Director General for Coastal Safety and Salvage Administration salvors discharged 8,900 tonnes of cargo into lightening vessels to re-float her. The quantity of cargo unloaded equated to a bodily reduction in draught of about 1.43 metres, which should have suggested that the actual depth of water was considerably less than was charted.

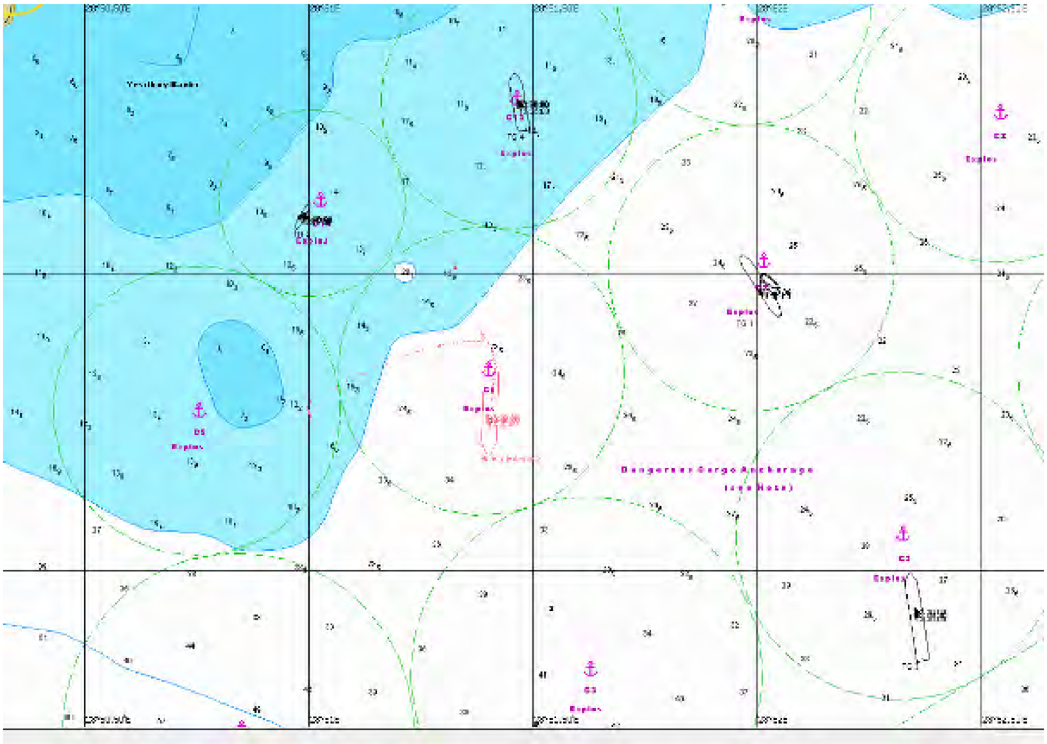


Figure 24. Orientation of the "Charlie flammable cargo and explosives anchorage" while the British enterprise was stationary

The Russian flag tanker Marshal Vasilevskiy, loaded with a cargo of 52,000 tonnes of heavy fuel oil, ran aground while heading on a course of 066º in C5 anchorage on 30 November 2001. Marshal Vasilevskiy had a length of 242 metres, and she had overshot her intended anchoring position. The vessel's draught was 11.88 metres and, whereas there was no sounding indicated at the precise grounding position, the chart gave the impression that a depth of about 13 metres could be expected. The salvage of Marshal Vasilveskiy took approximately 7 days and was carried out by the state salvors. The port authority investigated this accident and assessed that the cause was clearly navigational error and therefore no further investigation, including a survey of the seabed, were necessary. Again, a valuable opportunity to identify this uncharted shoal was missed. It can be seen from the Bridge Simulator chart in Figure 24 that the shoal is now charted, however the *British Enterprise* was not aware. Despite two previous major groundings on the bank in C5 anchorage in recent years, the existence of the bank was only reported after the grounding of *British Enterprise*, despite there being a discrepancy on each occasion between the vessels' draughts and the charted depth.

Given that this information should have been known to the crew and certainly was known to the local port authority, the BN model can be further modified to provide an assessment on the potential for a grounding accident if all known information is considered. Table 20 outlines the nodes and states in the BN that have been updated in light of the information that was known by the port authority. It can be seen that the states of nodes “Familiarity with Navigational Area”, “Quality of Equipment and Facilities” and “Availability of Equipment and Facilities” have been updated but from a negative perspective (*Inadequate, Inconvenient* and *No* respectively) to demonstrate that the crew were clearly unfamiliar with the anchorage area, and the quality and availability of key equipment and facilities was not good enough. i.e., updated navigational charts. Furthermore, 3 nodes under “Unsafe Supervision” have been updated to reflect that in fact the “Voyage Planning” and “Manoeuvre and Operation Planning” were now unsafe and that the VTS and local port authority failed to correct a know problem. Finally, the external condition of “Shallow Water” is now updated to “100%-Yes”. Thus, with all known information, the probability of contact, collision and grounding consequences increase by 6% 8% and 6% respectively (39%, 45% and 39%). This increase magnitude, given the knowledge that should have been known prior to manoeuvring operations, clearly indicates that an alternative course would have been plotted out of anchorage C6 that would have avoided the shallow water in anchorage C5.

Table 20. Updated nodes and states in the BN model relating to additional information known by the local port authority.

Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with Ship	Adequate	95%	100%	5%
Familiarity with Navigational Area	Inadequate	10%	100%	90%
Personnel Education and Training	Adequate	19%	100%	81%
Quality of Equipment and Facilities	Inconvenient	2%	100%	98%
Availability of Equipment and Facilities	No	72%	100%	28%
Ergonomic Design	Convenient	98%	100%	2%
Company's Manning Strategy	Optimum	9%	100%	91%
Port and Company Pressure	No	98%	100%	2%
Unsafe Supervision - Cause				
Voyage Planning	Unsafe	27%	100%	73%
Manoeuvre and Operation Planning	Unsafe	40%	100%	60%
Correcting a Known Problem	Unsuccessful	38%	100%	62%
Operational Conditions - Cause				
Navigational Area	Anchorage	66%	100%	34%
VTS Sector	Kadikoy	32%	100%	68%
Ship type	Tanker	9%	100%	91%
Ship Length	LOA101-200m	39%	100%	61%
Ship age	Below10years	19%	100%	81%
Visibility	Good above5nm	90%	100%	10%
External Conditions Affecting Ship Motion	Yes	32%	100%	68%
Local Traffic	Medium	40%	100%	60%
Transit Traffic	Low	35%	100%	65%
Port Traffic	Low	80%	100%	20%
Sharp turn	Yes	52%	100%	48%
Narrow Channel	No	50%	100%	50%
Shallow Water	Yes	48%	100%	52%
Consequence - Effect				
Contact	Occur	33%	39%	6%
Collision	Occur	37%	45%	8%
Grounding	Occur	33%	39%	6%

4.5 Collision accident in Istanbul Strait: Tanais Dream (Bulk) and Sultanahmet (Ferry)

4.5.1 Brief Narrative

A Belizean flagged bulk carrier *Tanais Dream* collided with a Turkish flagged car ferry *Sultanahmet* in front of Sarayburnu, Istanbul Strait on 18th of December2014 at 19:39:50. As a result of the accident, both vessels were damaged and there was no loss of life, a serious injury or an environmental pollution. The *Tanais Dream* entered into the Istanbul Strait on 18th of December 2014 at 18:15 to carry its' 27,400 M/T clay, which was loaded in Illichivsk/Ukraine, to the Spanish port of Castellon. *Tanais Dream*, which preferred to cross the Istanbul Strait without taking a marine pilot, proceeded without any problems to off of the Maiden's Tower. The *Sultanahmet* car ferry departed from Harem Pier at 19:32 to carry out its' voyage on the Harem - Sirkeci line. At 19:39:50, *Tanais Dream* hit with its' stem *Sultanahmet* from its' port side by contact in front of Sarayburnu in the traffic lane in south direction (west) of traffic separation scheme inside the Istanbul Strait. After the collision, especially *Sultanahmet* was damaged at a level that may be regarded as serious from its portside and luckily, there was no death or serious injury. After the accident, *Sultanahmet* continued to carry out its voyage and delivered the passengers and vehicles safely to the Port of Sirkeci, and *Tanais Dream* dropped anchor in front of Istanbul Ahırkapı in line with the instructions of the Vessel Traffic Services (VTS) Centre.

4.5.2 BN Analysis: Collision – Perspective of Tanais Dream

Given the information presented in the accident report on the collision between *Tanais Dream* & *Sultanahmet* [144], the BN for the Istanbul Strait (see Figure 22) was updated to reflect the known information. In this case the evidence inserted into the BN model is what the master of the vessel, *Tanais Dream* knew at the time while in transit through the Kadikoy VTS Sector. Table 21 demonstrates the nodes in the BN where evidence has been altered, as well as the specific state of the node that has been updated, the prior occurrence based on all accidents, and the new evidence value based on the British Enterprise Operational Conditions and Organisational Influences.

It can be seen from Table 21 that given the Organisational Influences and the Operational Condition (both Internal and External) that their risk of a collision decreases by 5%. If this dynamic risk control tool was in place at the time of the voyage, then it would be noted that he main contributing factors to a potential collision would be the high local traffic, the day status (night) combined with operation in a narrow channel. Similarly, there is nothing to suspect that the organisational influences have a major effect on the outcome of a collision as the company policy and the operating crew were more than adequate for the passage. Therefore, unless a major failure or error by the crew occurs, then a collision should be easily avoided.

Table 21. Updated nodes and states in the BN model relating to known information by the crew of the Tanais Dream.

Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with Ship	Adequate	95%	100%	5%
Familiarity with Navigational Area	Adequate	90%	100%	10%
Personnel Education and Training	Adequate	19%	100%	81%
Quality of Equipment and Facilities	Convenient	98%	100%	2%
Availability of Equipment and Facilities	Yes	38%	100%	62%
Rules and Procedures	Adequate	96%	100%	4%
Ergonomic Design	Convenient	98%	100%	2%
Company's Manning Strategy	Optimum	99%	100%	1%

Port and Company Pressure	No	98%	100%	2%
Operational Conditions - Cause				
Navigational Area	Navigation	34%	100%	66%
VTS Sector	Kadikoy	32%	100%	68%
Ship type	Dry Cargo	72%	100%	28%
Ship Length	LOA101-200m	55%	100%	45%
Ship age	Age 11and 20	11%	100%	89%
Visibility	Good above5nm	90%	100%	10%
External Conditions Affecting Ship Motion	No	68%	100%	32%
Local Traffic	High	45%	100%	55%
Transit Traffic	Medium	45%	100%	55%
Port Traffic	Low	80%	100%	20%
Sharp turn	Yes	52%	100%	48%
Narrow Channel	Yes	50%	100%	50%
Shallow Water	No	50%	100%	50%
Day Status	Night	64%	100%	36%
Consequence - Effect				
Contact	Occur	33%	27%	-6%
Collision	Occur	37%	32%	-5%
Grounding	Occur	33%	27%	-6%

4.5.3 BN Analysis: Collision – Perspective of Sultanahmet.

Given the information regarding the collision accident, there are certain pieces of information and facts that were available before the departure the car ferry *Sultanahmet* from the western side of the IS, and its crossing of the strait to the east bank. This information is inserted into the BN and is demonstrated in Table 22. The following information was known to the crew of the *Sultanahmet* prior to the voyage and thus has been incorporated into the BN under Organisational Influences and Unsafe Supervision.

- The masters have difficulty to engage with something else by not looking ahead because the masters control the vessel by sitting, and sometimes using their two hands due to the structure of the vessel *Sultanahmet*, the period and distance of navigation is short, they continuously cross the traffic separation scheme, and the vessels navigating in the area continuously make a change in their courses and speed and this situation has a negative effect for the masters to make observations from AIS and radar.
- As it can be seen in the courses recommended with departure from Haydarpaşa and Kadıköy and destination as Eminönü-Karaköy in Harbour Master of Istanbul Local Maritime Traffic Guide, it is recommended that the vessel rise up to offshore of the Maiden's Tower and cross the Traffic Separation Scheme at 90°. However, the vessel *Sultanahmet* tried to cross the traffic separation lines using the shortest route by crossing the TSS at approximately 45°.
- It is considered that the blind spot on the bridge of the vessel *Sultanahmet* has a negative effect to the ergonomics and the field of vision of the masters.

Table 22. Updated nodes and states in the BN model relating to known information by the crew of the Sultanahmet before the collision.

Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with Ship	Adequate	95%	100%	5%
Familiarity with Navigational Area	Adequate	90%	100%	10%
Personnel Education and Training	Adequate	19%	100%	81%

Quality of Equipment and Facilities	Convenient	98%	100%	2%
Availability of Equipment and Facilities	Yes	38%	100%	62%
Rules and Procedures	Adequate	96%	100%	4%
Ergonomic Design	Inconvenient	2%	100%	98%
Company's Manning Strategy	Optimum	99%	100%	1%
Port and Company Pressure	No	98%	100%	2%
Unsafe Supervision - Cause				
Voyage Planning	Unsafe	34%	100%	66%
Operational Conditions - Cause				
Navigational Area	Navigation	34%	100%	66%
VTS Sector	Kadikoy	32%	100%	68%
Ship type	RO-RO	3%	100%	97%
Ship Length	LOAbelow100m	39%	100%	61%
Ship age	Age below10	19%	100%	81%
Visibility	Good above5nm	90%	100%	10%
External Conditions Affecting Ship Motion	No	68%	100%	32%
Local Traffic	High	45%	100%	55%
Transit Traffic	Medium	45%	100%	55%
Port Traffic	Low	80%	100%	20%
Sharp turn	No	48%	100%	52%
Narrow Channel	Yes	50%	100%	50%
Shallow Water	No	50%	100%	50%
Day Status	Night	64%	100%	36%
Consequence - Effect				
Contact	Occur	33%	21%	-12%
Collision	Occur	37%	25%	-12%
Grounding	Occur	33%	21%	-12%

It can be seen from Table 22 that the risk of a collision is less likely than with the information and vessel parameters of *Tanais Dream*, despite the poor ergonomics and unsafe voyage planning of the *Sultanahmet*. This is most likely due to the data that is used when constructing the BN. It is noted that only 3% of all sinking, grounding, and collision/contact accidents, in the IS, involve a Ro-Ro ferry but 72% involve a Dry-Bulk carrier. Therefore, the reaction of the model is that the risk of a Ro-Ro causing or being involved in a collision is much less likely than a Dry-Bulk carrier. Yet in this situation, and based on the accident report, it was the *Sultanahmet* that caused the accident. Thus, some other combination of factors must have occurred for the collision to take place. When the particulars of the accident are broken down, it can be seen that there certainly were other factors known to the crew and the master of the *Sultanahmet* during their voyage that, if addressed, could have avoided the collision.

The following information and factors will now be considered in the BN of the IS to determine the actual likelihood of the collision if all factors and parameters were taken into account. The following information is considered under the following HFACS categories: Unsafe Supervision, Preconditions for Unsafe Acts and Unsafe Acts.

- It is considered that the master of the *Sultanahmet* vessel did not keep an effective lookout during the navigation and did not benefit from the AIS and radar in this regard before and during the navigation, and therefore, he realized the vessel *Tanais Dream* very late.
- It was determined that there was no seaman assigned as a lookout on the bridge onboard *Sultanahmet* during the collision.
- The vessel *Sultanahmet* acted against the regulations on that crossing shall be made from the stern of the vessels passing through as much as possible and that the sterns and boards of the

vessels passing through the Strait shall not be approached more than 0,5 cable length.

- It is considered that the chief engineer of the vessel *Sultanahmet* did not keep an effective lookout which is in his job definition.
- Furthermore, although there is no proof such as a medical report on the how much the stomach problem the master suffered before the accident at home may have affected him mentally and physically, it is considered that this situation may have caused him a medical and psychological distress.

Table 23 addresses the additional information stated above. It can be seen that the risk of a contact, grounding and collision all decrease by 5% each (28%, 32% and 28% respectively). This is unusual as the additional factors under Unsafe Supervision, Preconditions for Unsafe Acts and Unsafe Acts must surely contribute to a collision accident. It has been previously noted how little and effect the ship type may have on the outcome of the likelihood of the consequences due to Dry-Bulk contributing to 72% of the accident sin the IS (Container -19%, Tanker-9%, RoRo-3%, Passenger-2% and other-1%). However, if this parameter is removed and the vessel type is not taken into account, just the standard parameters of the Operational Conditions (Navigational Area, VTS Sector, Ship Length, Ship age, Visibility, External Conditions Affecting Ship Motion, Local Traffic, Transit Traffic, Port Traffic, Sharp turn, Narrow Channel, Shallow Water and Day Status) along with the other factors in Table 23, then the consequence likelihood changes drastically. Without the vessel type in consideration, and considering all other parameters from the collision accident, the likelihood of a collision, which should have been addressed before the collision, becomes 51%, an increase of 14% (Grounding and Contact both at 44% - an increase of 11%). Thus, a collision was likely to occur regardless of the vessel type and could have been avoided.

Table 23. Updated nodes and states in the BN model relating to known information by investigating authorities regarding the Sultanahmet following the collision.

Nodes	Node State	No Evidence	Evidence	Change
Organisational Influences - Cause				
Familiarity with Ship	Adequate	95%	100%	5%
Familiarity with Navigational Area	Adequate	90%	100%	10%
Personnel Education and Training	Adequate	19%	100%	81%
Quality of Equipment and Facilities	Convenient	98%	100%	2%
Availability of Equipment and Facilities	Yes	38%	100%	62%
Rules and Procedures	Adequate	96%	100%	4%
Ergonomic Design	Inconvenient	2%	100%	98%
Company's Manning Strategy	Optimum	99%	100%	1%
Port and Company Pressure	No	98%	100%	2%
Unsafe Supervision - Cause				
Voyage Planning	Unsafe	27%	100%	73%
Watch Planning	Unsafe	27%	100%	73%
Correcting a Known Problem	Unsuccessful	38%	100%	62%
Monitoring of Seafarers' Performance and Quality standards	Inadequate	46%	100%	54%
Preconditions for Unsafe Acts - Cause				
Stress	Yes	47%	100%	53%
Situational Awareness	Lack	50%	100%	50%
Communication and Coordination	Inadequate	45%	100%	55%
Engagement in Other Tasks	Yes	37%	100%	63%
Unsafe Acts - Cause				
Violations	Yes	52%	100%	48%

Perceptual Based Error	Yes	56%	100%	44%
Operational Conditions - Cause				
Navigational Area	Navigation	34%	100%	66%
VTS Sector	Kadikoy	32%	100%	68%
Ship type	RO-RO	3%	100%	97%
Ship Length	LOAbelow100m	39%	100%	61%
Ship age	Age below10	19%	100%	81%
Visibility	Good above5nm	90%	100%	10%
External Conditions Affecting Ship Motion	No	68%	100%	32%
Local Traffic	High	45%	100%	55%
Transit Traffic	Medium	45%	100%	55%
Port Traffic	Low	80%	100%	20%
Sharp turn	No	48%	100%	52%
Narrow Channel	Yes	50%	100%	50%
Shallow Water	No	50%	100%	50%
Day Status	Night	64%	100%	36%
Consequence - Effect				
Contact	Occur	33%	28%	-5%
Collision	Occur	37%	32%	-5%
Grounding	Occur	33%	28%	-5%

This Dynamic BN analysis has demonstrated that groundings, collision/contact and sinking accidents can be somewhat predicted or a least heighten awareness of a potential incident given the evaluation of previous marine accidents. What can be said is that the Ship type should really play a major role in likelihood of a marine accident but should display a contributing role in the type of consequence dependant on the cargo, for example pollution or ignition. Thus, in terms further work, the BN can be improved and adapted to optimise the predictions of grounding, collision/contact and sinking accidents, but also modified to further examine the additional consequences based on different vessel types and the nature of the cargo that they carry.

5 Evaluation of Risk Control Measures (RCMS) through Decision Theory

When developing a decision-making methodology, it is important to clearly define the domain that it is to represent. The criteria must be appropriately allocated, with careful attention being paid to what each criterion shall represent and where they shall rank in the evaluation hierarchy. The fundamental part of developing a coherent decision-making method, with the ability to deliver coherent results, lies in its evaluation hierarchy and the allocation the belief degrees and weights. With this in mind, a decision-making method has been established to ascertain the most suitable Risk Control Measures (RCM) for application in the IS. The DS was initially considered; however, the experts did not return any meaningful suggestions to improve the safety of navigation through the DS. This is reflected in the number of accidents in the DS when compared to the number of accidents in the IS. To ensure that a coherent method was established, knowledge was obtained through reviewing literature and conversing with industrial experts.

There are a number of steps involved in the procedure for applying a decision-making algorithm to a problem. Having a number of steps is key for maintaining consistency throughout the process and offers and element of confidence to the final analysis. There are key elements that the procedure must follow, these are outlined as follows.

5.1 Establish the domain and definition.

This involves putting boundaries in place in order to prevent the process from becoming too complex. It has already been stated in Section 2 that the RCMs shall be focused on the IS, particularly in high rik areas.

5.2 Identify the objective.

This involves stating what results are to be expected to be achieved from the problem-solving process. For this procedure and analysis, the goal is to determine the most suitable Risk Control Measures (RCM) for application in the IS based upon a set of criteria related to the HFACS and BN analysis conducted in Section 3 and 4. Furthermore, the evidential reasoning approach is utilised for the decision-making process. The first 2 steps of the decision-making methodology have been followed and identified in Sections 2, 3 and 4.

1.1 Identify a set of criteria relative to the problem.

In this section, the Risk Control Measures (RCMs) of the three nodes with the highest probability at each HFACS-PV level in the IS Accident network have been determined by expert opinions to reduce the risk. These measures are only suggestions, and besides being put forward qualitatively, they are listed with the ER approach, one of the MCDA methods. This application aims to evaluate the effectiveness of the measures on the nonconformities that cause grounding, collision/contact and sinking accidents. Thus, the feasibility of the measures, albeit empirical, is made, and it becomes possible to compare them with each other. The measures and the BN nodes that are thought to be affected by these measures are presented below. In order to apply the ER method, first of all, the evaluation criteria must be classified, and the MCDA structure must be established. As stated previously, the ER structure is based on the HFACS-PV and the Accident network (Figure 25). In this way, consistency between the IS Accident network structure and the ER structure has been ensured. In addition, since the effectiveness of the measure will be evaluated directly on the nodes in the network, it is easier to understand, interpret and compare.

5.2.1 Measure 1. Rearrangement of anchoring areas

This measure refers to the reorganization of the current anchorage areas (arrangement, capacity, and position) in IS with the joint work of the coastal authorities (Ministry of Coastal Safety, Transport, and Infrastructure), the Turkish Straits Research Centre and other units with an opinion. With this arrangement, especially the Anchorage Area B, where dry cargo ships anchor, can be expanded. Anchorage Area A, which is very close to the entrance of the IS, can be placed in a clearer position. In this measure, it is not concluded how the arrangement should be made and how the end positions of the anchor areas should be. This process can only be managed and concluded with the participation and effort of the relevant parties of Turkish Maritime. This application has revealed which nodes in the Accident network can be resolved if the anchorage points can be rearranged and their density can be reduced. The potential nodes that this measure may affect are Availability of Equipment and Facilities, Familiarity with the Area, and Traffic Density.

5.2.2 Measure 2. Rearrangement of separation scheme

Turkish Straits vessel traffic order (traffic separation lines) was established in 1998. Since this date, ship traffic has increased in the Turkish Straits. As a result, many factors that closely affect maritime traffic (vessel traffic operation standards, volume of port traffic, volume of domestic maritime traffic, etc.) have also changed. For this reason, if the traffic separation line, especially the sections between Sector

Marmara-Sector Kadikoy-Sector Kandilli, can be reviewed, some of the nodes in the accident network can be taken under control. In line with expert opinions, this measure is thought to be effective on the nodes, Availability of Equipment and Facilities, Manoeuvre and Operation Planning, Errors, and Traffic Density.

5.2.3 Measure 3. Passage and anchorage with a pilot

In the current situation, the decision to take the pilot is optional (except for ships carrying dangerous goods over 200 meters and special type of ships) during the IS transit. Also, pilotage is not compulsory for the ships which anchor in the IS while waiting for supply or entrance to the strait. Compulsory pilotage can be applicable in narrow waterways such as the Singapore Strait, where the traffic and anchorage areas are dense (where ships are anchored close). As a result of this practice, operations can be carried out in a safer manner. Considering that accidents at anchorage areas are relatively rare in the Singapore Strait, it was thought that a similar practice would be beneficial in the IS. Therefore, this measure was also evaluated with the ER approach. Passage and anchorage with pilot, if implemented as intended, can positively affect, Personal Education and Training, Availability of Equipment and Facilities, Familiarity with the Area, Manoeuvre and Operation Planning, Situational Awareness, Management, Leadership and Guidance, Errors, Violations, Weather, Sea and Visibility, Locational Restrictions.

5.2.4 Measure 4. Stand by tug assistance

This measure is aimed at keeping the sudden inconveniences under control, which may arise during the transit through the IS. In the IS, there are sharp turns and points where the current regime is irregular in every sector. Failures and malfunctions that occur suddenly at these points directly affect the occurrence of accidents. In order to prevent this, tugboats can be kept ready in areas close to the dangerous points of the strait (Kandilli and Yenikoy turn, etc.) during the passage of high risk ships (old, full length over 200 meters, dry cargo, etc.). As soon as the failure occurs, tug can move towards the ship, preventing the accident or reducing the severity of the accident consequence. In both cases, it plays an important role in reducing the risk. Nodes that this measure may affect if implemented as intended are Nonconformities and Failures Preventing the Ship's Motion, Locational Restriction, External Conditions Effecting Ship's Motion.

5.2.5 Measure 5. Strait-specific, certified training

Although not required by the coastal state, many international shipping companies provide certified training to ship masters who will pass through the Singapore Strait. Thanks to this training, ship masters learn the operation of the traffic scheme, reporting systems, weather and sea conditions, local dynamics (narrow points, sharp turns, etc.) from the pilots who are experts in the area before they pass through the area. If this application is encouraged in the nodes may be positively affected are Availability of Equipment and Facilities, Familiarity with the Area, Safety Culture, Situational Awareness, Management, Leadership and Guidance, Communication and Coordination, Errors, Violations, Weather, Sea and Visibility, Locational Restrictions.

5.2.6 Measure 6. Using the dynamic risk assessment model

This measure refers to use the “Accident network” structure presented in the study as a risk assessment model (Developed and utilised in Section 4). In this way, ship masters and vessel traffic system operators will be able to observe the change of the ship's probability of accident during the transit or anchorage operation in the IS. In this way the operators will be aware of which nodes may pose a greater risk for the particular ship. By using this awareness, operators will be able to take operational decisions such as whether tugboat escort is required for the relevant ship, speed limitation or piloting advice more accurate. In case the accident network is used as intended nodes such as Familiarity with the Area, Safety Culture, Manoeuvre and Operation Planning, Correcting a Known Problem, Situational Awareness, Management, Leadership and Guidance, Communication and Coordination, Errors, Violations, Internal Conditions, Locational Restrictions are thought to be positively affected.

5.2.7 Measure 7. Visual monitoring of Strait's traffic with remote monitoring systems

In all of the narrow waterways examined, the vessel traffic area is monitored by radar. In addition, the movements of the ships are tracked on the electronic map using AIS. These two systems are extremely useful for both ship masters passing through the area and vessel traffic operators regulating the traffic. However, these systems are two-dimensional systems and both systems have disadvantages. Some of the disadvantages of the radar system are that small boats are relatively difficult to spot, and weather conditions directly affect the radar performance. The fact that not all ships are equipped with AIS or that they are closed for various reasons, and that there are shifts between the AIS position and the actual position are examples of the disadvantages of electronic map tracking. For this reason, it is possible to monitor the traffic area 24/7 in three dimensions by using the developing remote sensing and imaging technologies (satellite, 5th generation base stations (5G), mobile technologies, cameras, and cloud systems). Such a system will play a major role in increasing not only navigational safety, but also environmental safety. For this reason, how the continuous visual monitoring of the IS with remote imaging technologies will affect the accidents has also been examined with the ER approach. The nodes that this measure can positively affect are Operation Management, Oversight and Control, Manoeuvre and Operation Planning, Correcting a Known Problem, Communication and Coordination, Violations, and Traffic Density.

5.2.8 Measure 8. Ship-specific, certified training

Refers that bridge and engine room team members be provided with familiarity training prior to joining the ship. Similar training programs are implemented by many maritime companies today without a certificate. The trainings that will be given by the training departments of the maritime companies and will be subject to renewal at regular intervals will increase the familiarity of the team members. In these trainings, not only the use of the equipment on the ship, but also the previous port state control and internal audit non-compliances, the previous similar accident and incidents should also be included. This measure aims to reduce the lack of familiarity with the ship and BRM-based non-compliances. Ship-specific training; Personal Training, Familiarity with Ship, Operations Management, Oversight and Control, Situational Awareness, Management, Leadership and Guidance, Communication and Coordination, Errors, Internal Conditions, Locational Restrictions are thought to be positively affect nodes as a result of implementation of this measure.

5.2.9 Measure 9. Right to pass without a pilot, depending on the number of annual passages

Today, the right of passage without a pilot from risky ships (longer than 200 meters, carrying dangerous cargo, etc.) to pass through the IS is left to the ship's master. Due to economic concerns and keeping the speed of operation high, only half of the ships transiting in 2020 received a pilot. In this measure, it is expressed that the right of passage without taking pilot is given to the masters of the ships who will make the passage as an alternative, according to their navigation experience in the Turkish Straits. In this way, the condition that it is necessary to have a certain experience in order to pass without a pilot will be confirmed to some extent. Here, it would be appropriate to determine a minimum value according to the number of passes and the number of passes in recent years in order to determine that the experience of the ship's master is sufficient and up-to-date. For example, it can be considered as having made at least 10 passages through the Turkish Straits and having passed at least once in the last 1 year. In this way, if the master of the ship is really experienced in the straits, he will have the right to pass without a pilot. Right to pass without a pilot, depending on the number of annual passages may have positive effect on nodes such as Familiarity with the area, Manoeuvre and Operation Planning, Correcting a Known Problem, Situational Awareness, Management, Leadership and Guidance, Communication and Coordination, Errors, Locational Restrictions.

Alternative Name

- Rearrangement of anchoring areas
- Rearrangement of seperation scheme
- Passage and anchorage with a pilot
- Stand by tug assistance
- Strait-specific, certified training
- Using the dynamic risk assessment module
- Visual monitoring of Strait's traffic with remote monitoring systems
- Ship-specific, certified training
- Right to pass without a pilot, depending on the number of annual passages

- Istanbul Strait Nonconformities (HFACS-PV/BA)
  - Organizational Influences
    - Resource Management
    - Organizational Climate
    - Organizational Process
  - Unsafe Supervision
    - Inadequate Supervision
    - Planned Inappropriate Operations
    - Failed to Correct a Known Problem
  - Preconditions for Unsafe Acts
    - Substandard Team Members
    - Technology and Interface Malfunctions
  - Unsafe Acts
    - Errors
    - Violations
  - Operational Conditions
    - Internal Conditions
    - External Conditions

- Istanbul Strait Nonconformities (HFACS-PV/BA)
  - Organizational Influences
    - Resource Management
      - Personal Education and Training
      - Crew Assignment
      - Equipment and Facility Resources Management
        - Availability of Equipment and Facilities
        - Quality of Equipment and Facilities
        - Ergonomic Design
      - Familiarity with the Ship
      - Company's Manning Strategy
      - Familiarity with the Navigation Area
    - Organizational Climate
      - Safety Culture
      - Port and Company Pressure
    - Organizational Process
      - Operation Management
      - Legal Shortcomings
      - Oversight and Control
  - Unsafe Supervision
    - Inadequate Supervision
      - Internal and External Audits
      - Tracking of Seafarers' Performance and Quality Standards
      - Planned Maintenance
      - Tests and Monitoring
    - Planned Inappropriate Operations
      - Maneuver and Operation Planning
      - Voyage Planning
      - Watch Palnning
      - Hours of Work and Rest
    - Failed to Correct a Known Problem
  - Preconditions for Unsafe Acts
    - Substandard Team Members
      - Situtational Awareness
      - Management, Leadership and Guidance
      - Drug, Alcohol and Medication Effect
      - Stress
      - Communication and Coordination
      - Confidence on Devices and Self
      - Engagement in Other Tasks
      - Workload
      - Fatigue
    - Technology and Interface Malfunctions
  - Unsafe Acts
    - Errors
      - Skill Based
      - Decision Based
      - Perceptual
    - Violations
  - Operational Conditions
    - Internal Conditions
      - Nonconformities and Failures Preventing the Ship's Motion
      - Ship's Age
      - Ship's Type
      - Ship's Length
    - External Conditions
      - Weather, Sea and Visibility
        - Reducing Visibility
        - Effecting Ship's Motion
      - Locational Restrictions
        - Type of Navigation
        - VTS Sector
        - Traffic Density
          - Local Traffic
          - Transit Traffic
          - Port Traffic
        - Shallow Water
        - Sharp Turn
        - Narrow Channel Structure

Figure 25. ER structure for the IS based on HFACS-PV and accident network

5.3 Develop the belief degrees for ER analysis

It is assumed that the weighting factors of the criteria at the same level in the established ER structure are equal (1/total number of criteria at the same level). For example, under the Organizational Influences Level; The weight distributions of the Resource Management, Organizational Climate and Organizational Processes criteria were calculated as 1/3=0,3333. While establishing the structure, each measure outlined in the subsequent sections was considered as alternatives, in accordance with the general principle of MCDA. Experts were asked to evaluate the potential impact of each alternative on each evaluation criterion on a 3-point Likert scale (Does not affect, partially reduces, and eliminates). Since the experts evaluating the effectiveness of the alternatives were the same as those in the Spatial Analysis in Section 3 and the IS Accident network development in Section 4, the opinions were equally weighted. These five evaluation terms have been outlined, with Hn denoting the nth evaluation grade. This is demonstrated by Equation 6:

$$H_n = \{Does\ Not\ Effect\ (H_1), Partially\ Reduces\ (H_2), Eliminates\ (H_3)\} \tag{6}$$

It is supposed that there is a simple two-level hierarchy. Suppose there are L basic criteria e_j $(j=1\dots L)$ associated with general criterion E. Similarly, suppose the normalised weights of each general criterion are given as $\omega_1, \omega_2 \dots \omega_i \dots \omega_L$ $(i=1\dots L)$ where, ω_i is the relative weight of the i^{th} general criterion (E_i) with $0 \le \omega_i \le 1$ and ω_{ij} is the weight of the basic criterion (e_i) $0 \le \omega_{ij} \le 1$, where j represents the j^{th} basic criterion under the i^{th} general criterion. For example, the weighing of general criterion, Complexity, is represented by ω_i and the weight of the 3rd basic criterion under logistics, (Large Number of Cluster Heads, e_3) is represented by ω_{13}. See Figure 6 which outlines the evaluation hierarchy and contains the allocated notation related to the weighting of criteria. Furthermore, let $\beta_{n,i}$ denote the belief degree of the basic criterion e_i to the evaluation grade H_n, where $\beta_{n,i} \ge 0$ and $\sum_{n=1}^{N} \beta_{n,i} = 1$ Finally, $S(e_i)$ is the assessment of an alternative under criterion e_i,. This assessment can be represented by Equation 7 [145, 146, 147, 148].

$$S(e_i) = \{(H_n, \beta_{n,i}), n = 1, \dots, N\}\ i = 1, \dots, L \tag{7}$$

The assessment of a criterion, $S(e_i)$ is complete if the sum of the belief degrees is equal to 1, *i.e.* $\sum_{n=1}^{N} \beta_{n,i} = 1$.

5.4 Evidential Reasoning Algorithm and Data Aggregation

Suppose $m_{n,i}$ is the probability mass representing the degree to which e_i supports the hypothesis that the general criterion E is assessed to H_n, and is calculated by Equation 8 [145, 147, 148].

$$m_{n,i} = \omega_i \beta_{n,i} \quad n = 1, \dots, N \tag{8}$$

Similarly, for basic criteria, Equation 3 is rewritten as Equation 9:

$$m_{n,j} = \omega_{ij} \beta_{n,i} \quad n = 1, \dots, N \tag{9}$$

where, $m_{n,j}$ is the probability mass of the basic criteria e_j assessed to Hn. Also, $E_{I(j)}$ must be defined as the subset of the j basic criteria under the I^{th} general criterion, as given by Equation 10.

$$E_{I(j)} = \{e_1 \;\; e_2 \dots e_j\} \tag{10}$$

$m_{n,I(i)}$ is the probability mass defined as the degree to which all criteria in $E_{I(i)}$ support the hypothesis that E is assessed to the grade H_n. Similarly, $m_{H,\,I(i)}$ is the remaining probability mass which is unassigned to individual grades after all the basic criteria in $E_{I(i)}$ have been assessed. The terms $m_{n,I(i)}$ and $m_{H,\,I(i)}$ can be determined by combining the basic probability masses $m_{n,}$ and $m_{H,j}$ for all values of $n=1, \dots, N$ and $j=1, \dots, i$ [145, 147, 148]. Thus, the Evidential Reasoning algorithm is expressed through Equations 10, 11, 12, 13 and 14.

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{z=1 \\ z \neq t}}^{N} m_{t,I(i)} m_{z,i+1}\right]^{-1} \quad i = 1, \dots, L-1 \tag{11}$$

$$m_{n,I(i+1)} = K_{I(i+1)} \begin{pmatrix} m_{n,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1} \\ + m_{H,I(i)} m_{n,i+1} \end{pmatrix} \quad n = 1, \dots, N \tag{12}$$

$$m_{H,I(i+1)} = K_{I(i+1)} m_{H,I(i)} m_{H,i+1} \tag{13}$$

$$\beta_n = \frac{m_{n,I(L)}}{1 - m_{H,I(L)}}, \qquad n = 1, \dots, N, \qquad i = 1, \dots, L \tag{14}$$

where $K_{I(i+1)}$ is a normalising factor so that $\sum_{n=1}^{N} m_{n,I(i+1)} + m_{H,I(i+1)} = 1$ and β_n is the combined belief degree of the aggregated assessment for the criteria [145, 147, 148]

5.5 Utility Assessment and Ranking

The criteria must be ranked based upon their aggregated belief degrees from the ER algorithm. Suppose the utility of an evaluation grade, H_n, is denoted by $u(H_n)$. The utility of the evaluation grades is assumed to be equidistant as follows, with $u(H_1)=0$, $u(H_2)=0.5$, and $u(H_3)=1$, [149]. The estimated utility for the general and basic criteria, $S(e_i)$, is given by Equation 15 [145, 148].

$$u\big(S(e_i)\big) = \sum_{n=1}^{N} u(H_n) \beta_n \, (e_i) \tag{15}$$

5.6 *Case study: Application of RCMs with the Istanbul Strait Bayesian Network*

As a result of the ER application, the performance scores of the 9 measures made by the experts on the HFACS-PV levels were calculated in the IDS software. When the overall performance scores of the alternatives are evaluated, the most effective way is to passage and anchorage with a pilot (0.65) (Measure 3). Passage and anchoring with a pilot, respectively; has an impact on nonconformities under Unsafe Actions (0.90), Unsafe Supervision (0.77), Organizational Influences (0.66) and Preconditions for Unsafe Actions (0.57) (Figure 26). The presence of the pilot on the bridge can directly affect accidents by reducing the errors (0.99) and violations (0.85) that can be made by other bridge team members (Figure 27). At the Unsafe Supervision level, the pilot can disrupt the accident formation pattern by effectively correcting a known problem (uncharted shallow points, etc. in the area) (1.0) (Figure 27). A negativity arising from factors such as weather and geographical conditions will be clearly known by the pilot; because the master of the ship passes through the relevant area most frequently once a week or once a day, while the pilot passes several times per day. The impact of the Pilot on the Organizational Influences level is the safer management of Organizational Processes (0.94) (improper voyage and manoeuvre management, risk analysis and reviews) (Figure 27). The Pilot can have a positive impact on the level of Preconditions for Unsafe Actions by reducing (0.57) non-conformances emerging from Substandard Team Members (management activities, etc.) (Figure 27). Measure 3 has the least impact on Operational Conditions (0.22). This is due to the fact that it is often not possible to prevent the formation of Operational Conditions. However, since the pilot is experienced in the area, they can manage the operations more safely (0.54) in the presence of external conditions (bad weather, sea and visibility, etc.) that adversely affect the movement of the ship (Figure 27).

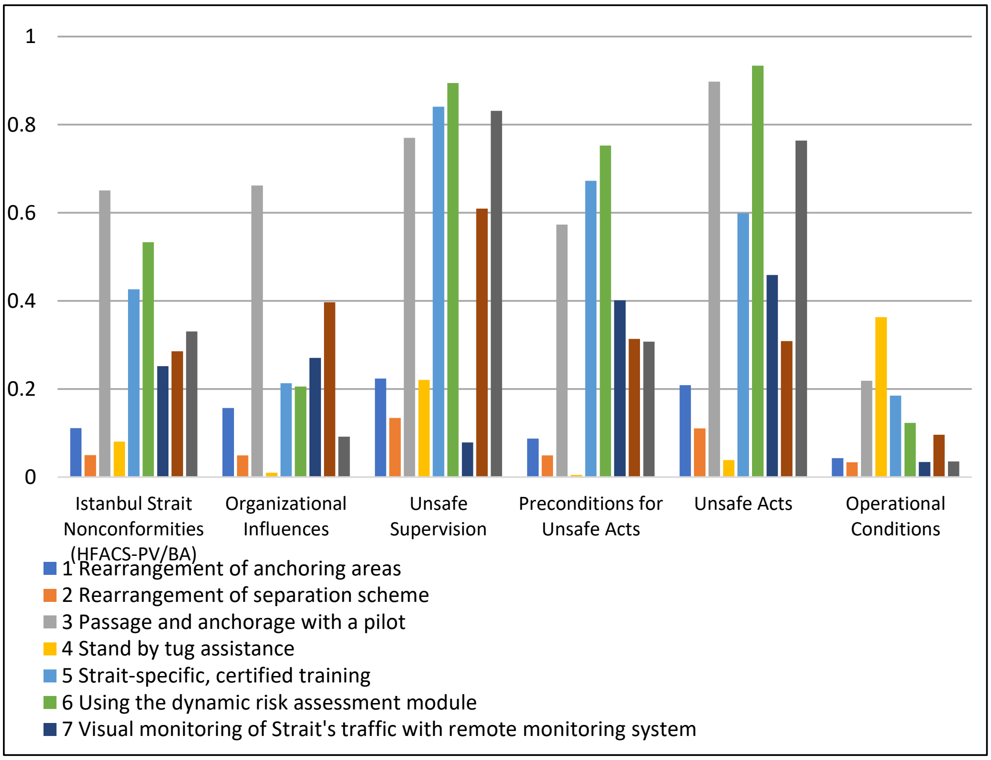


Figure 26. Performance distribution of measures for the IS on HFACS-PV main levels

Using the Dynamic Risk Assessment Model (Measure 6) developed as a result of this study is the second most effective (0.53) measure on HFACS-PV main levels, according to the ER results (Figure 26). Monitoring the risks of each passage by ship masters, pilots and vessel traffic operators will increase safety in the planning and implementation stages of operations. In addition, by using the model; The probability of nonconformities arising from Unsafe Actions (0.93), Unsafe Supervision (0.84) and Preconditions for Unsafe Actions (0.75) can be reduced (Figure 26). The positive impact at the Unsafe Actions level is a result of the fact that decision errors (0.99) and violations (0.90) can be reduced (Figure 27). Using the module can disrupt the pattern of accident occurrence by contributing the process of correcting a known problem at the Unsafe Supervision level (1.0) and reducing inappropriate planning (0.95) (Figure 27). If Measure 6 is applied properly, the awareness and alertness of the team members will be positively (0.75) affected, besides, vessel traffic operators will be able to give a direct warning in case of a possible loss of awareness (Figure 27). With a wide and comprehensive awareness, it is possible to break the chain of reaction which can be traceable by using the IS Accident network. The accident network model will serve for this purpose. Using the model will be least effective on non-conformities under the nodes; Organizational Influences (0.21) and Operational Conditions (0.12) (Figure 26). The main reason for this is that the accident network is not used in organizational (managerial) activities, but rather in operational and technical processes, which gives effective results.

Providing strait-specific certified training to ship masters or all bridge team members who will pass through the area (Measure 5) is the third most effective (0.43) measure on HFACS-PV main levels (Figure 26). With this training, team members will be able to acquire very important skills such as awareness about risks in the IS, risky areas, irregular current regimes, right behaviour in emergency situations, communication, and coordination. As a result of strait-specific training, respectively; Non-compliances under Unsafe Supervision (0.84), Preconditions for Unsafe Actions (0.67) and Unsafe Actions (0.60) can be mitigated. It is predicted that the training to be received from the experts will have a positive impact on the Unsafe Inspection level by reducing the inappropriate operation (cruising, drifting, anchoring) planning (0.90) (Figure 27). Under the Preconditions for Unsafe Actions level, a positive effect (0.67) can be made on the prevention of accidents by reducing the substandard situations (situational awareness) of team members and inappropriate management activities (loose team management) (Figure 27). The levels that are predicted to be least affected by strait-specific certified training are Organizational Influences (0.21) and Operational Conditions (0.18) (Figure 26). The pilots who have been working in the area for many years will be able to transfer their experience to the ship masters who will pass through the trainings they will give. In this way, their familiarity with the area will be increased.

The right to pass without a pilot, depending on the number of annual passages (Measure 9) is the fourth most effective (0.33) measure on the HFACS-PV main levels (Figure 26). The main purpose of this measure is to make sure that the master of the ship that will pass without a pilot is a person who really knows the characteristics and difficulties of the area. The right to pass without a pilot, depending on the number of annual passages is effective on nonconformities under; Unsafe Supervision (0.83), Unsafe Actions (0.76), Preconditions for Unsafe Actions (0.31) (Figure 26). The highest positive impact (0.89) at the Unsafe Supervision level is achieved by preventing inappropriate planning processes (Figure 27). The positive impact at the Unsafe Actions level will be possible by reducing decision errors (0.80) and violations (0.75) based on experience (Figure 27). While passing through the area, there are ships that do not listen to the local traffic radio channel, do not answer calls, and cannot contact the surrounding ships and sectors due to language problems. In such cases, the smallest disruptions result in major disasters. For this reason, pilotage service is extremely important especially in risky narrow waterways such as the IS.

Ship-specific certified training (Measure 8) has a fifth (0.29) impact on HFACS-PV major levels. The level at which Measure 8 is most effective is for non-compliances under Unsafe Supervision (0.61).

Improper ship-based operation planning (choice of anchorage area, speed, and optimum route the channel, etc.) will be reduced by increasing training and familiarity with the ship (0.66) (Figure 27). Other levels at which Measure 8 may be effective are Organizational Influences (0.38) are Preconditions for Unsafe Actions (0.31) and Unsafe Actions (0.31) (Figure 26). With the safer execution of Organizational Processes (0.92) (improper navigation and manoeuvre management), it may have a reducing effect on non-conformities below the Organizational Influences level (Figure 27). With the theoretical and applied ship-specific certified training, the tolerance of the team members against the emergencies (breakdowns, loss of power, etc.) encountered during the passage will increase (0.30) (Figure 27). It will be possible to reduce non-conformities related to situational awareness (0.31), perception disorders and errors (0.31) that may occur due to panic and stress (Figure 27).

Visual monitoring of Strait's traffic with remote monitoring systems (Measure 7) is the sixth effective (0.25) measure on HFACS-PV main levels (Figure 26). Monitoring the traffic with remote monitoring systems and, where necessary, recommending safe route and manoeuvre by vessel traffic operators will increase the safety of navigation. With the implementation of Measure 7, non-conformities under Unsafe Actions (0.46), Preconditions for Unsafe Actions (0.40), and Organizational Influences (0.27) will be reduced (Figure 26). It is predicted that Errors (0.49) and Violations (0.45), which are triggers of the accident reaction chain, can be reduced with continuous monitoring (Figure 27). By alerting the ships running into danger, team members' awareness can be increased (0.40) and the incidence of non-compliances under Preconditions for Unsafe Actions can be reduced (Figure 27). The non-compliances that will be least affected by remote monitoring are those under the Unsafe Supervision (0.08) and Operational Conditions (0.03) levels (Figure 26). The reason for this is that with remote monitoring, only emerging and visually symptomatic situations can be noticed and intervened. This is the most important difference from the mandatory pilotage (Measure 3), the pilot is a direct member of the bridge team and the ship. Therefore, navigation and anchorage with a pilot is more effective on navigational safety in narrow waterways.

According to ER results, rearrangement of anchoring areas (0.11), stand-by tugboat assistance in risky areas (0.08) and rearrangement of traffic separation scheme (0.05) have a lower effect on HFACS-PV non-conformities compared to other measures. However, when these measures are evaluated one by one; rearrangement of anchoring areas (Measure 1); appears to be effective on non-conformities emerging from Unsafe Supervision (0.22) and Unsafe Actions (0.21). Stand-by tugboat assistance in risky areas (Measure 4) may have a positive impact on non-compliances under, Operational Conditions (0.36) and Unsafe Supervision (0.22). Finally, rearrangement of traffic separation scheme (Measure 2) may have positive impact on non-conformities under, Unsafe Supervision (0.13) and Unsafe Actions (0.11).

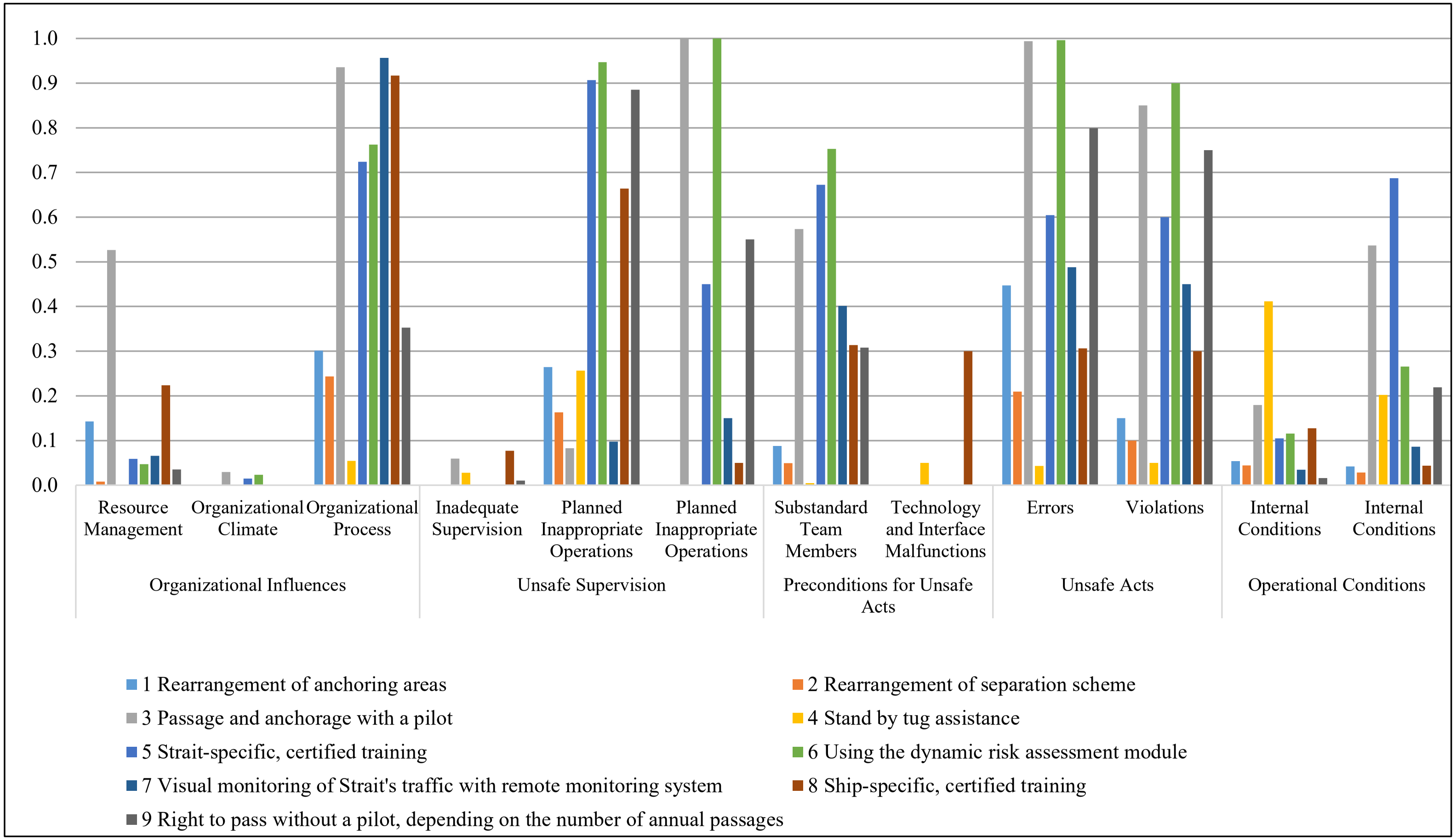


Figure 27. Performance distribution of the measures for the IS over the lower levels of HFACS-PV

6 Testing in Ship Simulator

In the final section of the report, the testing of the RCMs in the Bridge Simulator is presented. The Bridge simulator is part of the School of Engineering at Liverpool John Mores University and is a Navigational simulator Navi-Trainer Professional 5000 (NTPRO 5000) from Transas that enables simulator training and certification of watch officers, chief officers, captains, and pilots on all types of vessels. The Simulator utilises Transas ECDIS Software MNS 34 version 3.00.xx or later and complies with the latest IHO ENC Standard as well as IEC 61174:2015. Transas Marine Limited, as a manufacturer of Electronic Chart Display and Information System (ECDIS), adheres to compliance of the requirement of the SOLAS Regulation V/16 and MarED ADR GEN 017 and the Software Maintenance Regulation as stated in MSC.1/Circ. 1503 of the 24th of July 2015. Figure 28 shows the main 360^{O} Bridge Simulator, also known as Bridge 1. There are 4 additional smaller Bridge Simulators which are not 360^{O} and are used for training and scenarios where more than one vessel is required. Similarly, the smaller Bridge Simulators (2, 3, 4 & 5) all have the ability to run the same scenarios as Bridge 1 but without the 360^{0} view and in a smaller space. Figure 29 shows the orientation of the other Bridge Simulators, known from now on as Bridge 2. Furthermore, there is an instructor space where all simulations can be monitored and communications can be given through telecoms, i.e., advice for training or as a VTS, etc. This instructor suite is shown in Figure 30.

The testing in the simulator consists of two Case Study's which test Risk Control Measure 6 from the Er analysis in Section 5. This RCM was deemed to be the 2nd best option in terms of improving safety and reducing risk. Thus, the 2 case study's used in Section 4; the grounding of *British Enterprise*, and the Collision of *Tanais Dream* and *Sultanahmet* are to be recreated in the simulator and rerun using up to date knowledge from the accidents and from the dynamic risk model in Section 5.

Figure 28. a) view of the front of Bridge 1, b) view of the rear of Bridge 1, c) view to the left front of Bridge 1, and d) view to the front right of Bridge 1.

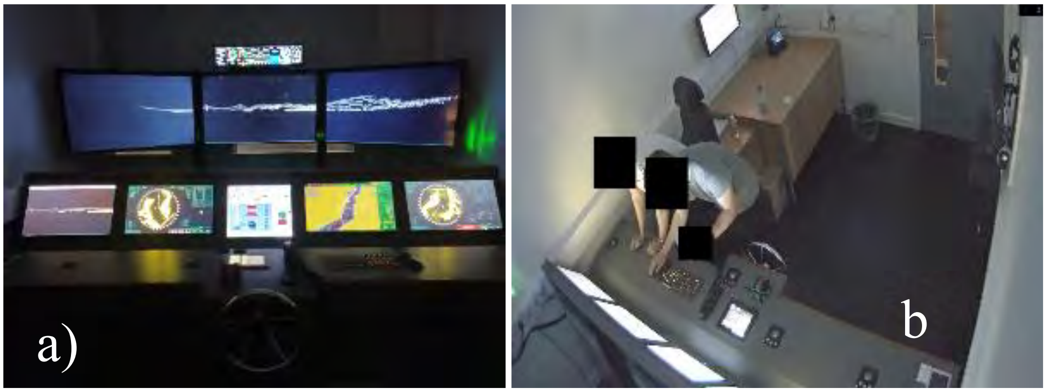


Figure 29. a) view of the front of Bridge 2, and b) view of the rear of Bridge 2.

Figure 30. a) Wall monitors in the instructor suite to observe and hear activity in each simulator through CCTV, as well as ECDIS and RADAR screens, and b) Desk monitors to view specific screens such as ECDIS and Radar, as well as the monitor the proximity of traffic, ship dynamics, ship logs, and ship forces.

6.1 Simulation of the Grounding of British Enterprise.

This exercise was conducted using the information provided in the accident report from MAIB. The brief narrative of the accident can be found in Section 4. The weather and sea conditions as well as the surrounding traffic was simulated in Bridge 1. Figure 24 has previously demonstrated the orientation of the anchorage of the *British Enterprise* in zone C6, with the surrounding vessels also in anchorage.

The first simulation was run through an automated programme with the particulars of the course plotted as well as the effects of the external conditions. This automated simulation was run multiple times with the external effects and the vessel grounded every time on the shallow area, however it did not ground in exactly the same spot each time due to the effects of the external environment. This highlights initially that the external conditions during his accident did indeed have an effect on the outcome of the manoeuvre. The simulation was the run again, however this time Bridge 1 would be used with a captain and a helmsman. This required two participants with sea going experience. Both participants are part of the team at LJMU, and their experience is as follows:

- Participant 1 (P1) – acting as the captain, has 12+ years of seagoing experience with at least 1 year as a captain. They have 5+ passages through the IS.
- Participant 2 (P2) – acting as the helmsman, has 10+ years of seagoing experience mainly in navigation and had never passed through the IS.

The Dynamic risk modelling o the *British Enterprise* grounding identified that had the local authority confirmed that there was a sallow area in anchorage C5 then the grounding would not occur and most likely the vessel would take a different route out of anchorage. However, in this Simulation the assumption was made that the *British Enterprise* had updated charts the shallow area and it was tested whether the route that the captain took was still safe enough to leave anchorage, avoid the stationary traffic and not run aground.

All of the parameters of the accident we updated in the simulator including the time that the vessel began to depart anchorage (at 13:35 with the anchor away at 13:43). The vessel lying to a northerly wind, and therefore it was necessary to turn her around to proceed to sea. As there were two vessels anchored on his starboard side in C2 and C7 anchorages, the master decided to swing the vessel around to port. This manoeuvre was completed in Bridge 1 with P1 and P2. Figure 31 shows the ECDIS visual of a) the vessel lifting the anchor and b) the vessel moving off anchorage and beginning to swing to port.

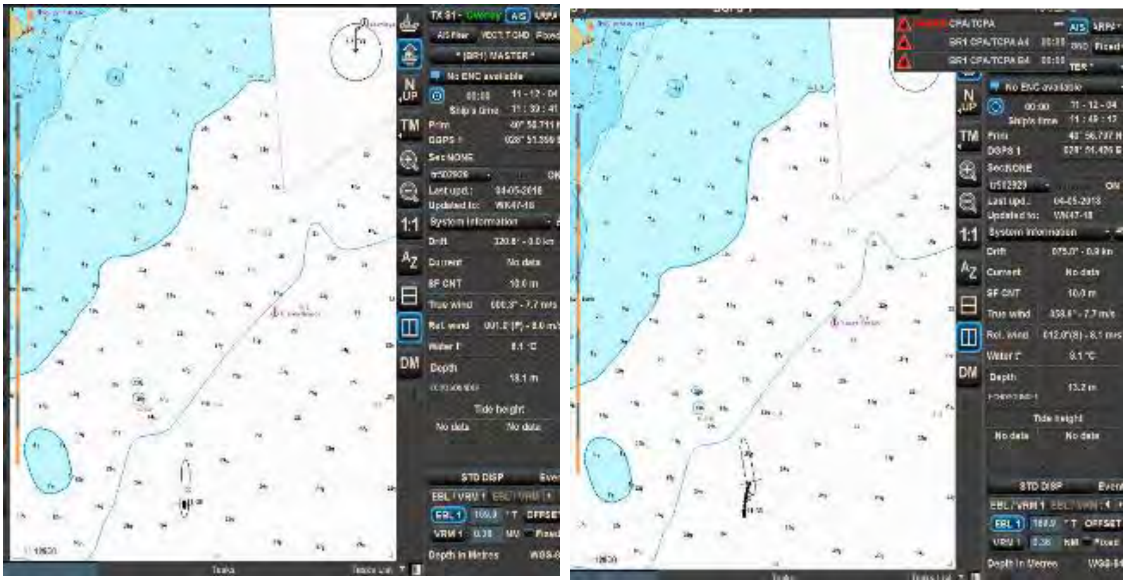


Figure 31. a) moving of anchorage and b) beginning the swing to port.

In the narrative from MAIB it states, "*….at about 13:50, the vessel had swung about 40º, and the master decided, rather than approach too close to the shallows inshore, to halt her forward movement. He ordered the helm to be placed amidships, and put the engine telegraph to slow, then half astern. At 1355, with the vessel at a safe distance from the charted shallows off Yesilkoy, the master stopped the engine and ordered the helm to be placed hard to port once again. He put the engine telegraph to half ahead and resumed swinging the vessel to port. Once British Enterprise's heading was about 240º, the master ordered the helmsman to begin steadying on that course*".

This set of instructions was followed almost to the exact minute as it occurred in the accident, however, the operation in the simulator changed at the order to steady on the course at 240^{O} while half ahead. Given that the shallow area is visible in the simulated scenario, it would not be possible to complete this manoeuvre without running aground. So P1 as Captain and P2 as helmsman made the decision to alter the narrative by making the turn much more gradual but maintained the same speed with the idea that they would be better off in terms of clearing the shallow area and passing through anchorage C5. Ultimately this did prove to be effective as the vessel was appearing to pass the shallow area, however as the vessel was completing the turn away from the shallows, the bow just ran aground. Figure 32 shows the approach to the shallows and the vessel finally stationary in the shallows. It can be seen in Figure 32 that the vessel has just touched the shallow area in Anchorage C5. Given the programming in the simulation, the scenario halts when a vessel is subject to a grounding or a collision/contact. Thus, an assumption can be made that if the simulated manoeuvre was made in the accident situation, the vessel may not have run aground as the shallow area is sand. It is also possible to say that the vessel would not have been ground for as long as she was in the accident scenario versus the simulated scenario.

Figure 32. a) vessel approaching the shallows appearing to potentially pass, and b) vessel grounded in the simulation.

This simulation in tandem with the results of the case study in the dynamic risk model has identified that had the chart been up to date the vessel could have potentially avoided grounding on the same passage out of anchorage. What is most certainly clear is that the external conditions i.e., the northerly wind, did in fact play more of a key role than anticipated.

6.2 *Simulation of the Collision between Tanais Dream and Sultanahmet.*

This exercise was conducted using the information provided in the accident report from EMSA (. The brief narrative of the accident can be found in Section 4. This simulation was conducted differently to the grounding scenario in Section 6.1. in this scenario cadets were used to run the accident as it happened, along with P2 from the grounding simulation. Figure 33 is taken from the spatial analysis and highlights where the collision took place in the Kadikoy VTS region of the IS. The scenario occurred at night, but the conditions were clear.

The setup for the simulation was that the accident parameters (operational conditions) would be simulated in bridge 1 and Bridge 2 simultaneously. The cadets and P2 would then split into pairs and use either Bridge 1 or Bride 2 where one would act as Officer of the Watch (OOW), and one would act as the lookout. The difference in this simulation is that the participants did not know it was a collision simulation. There were instructed to operate the Bulk Carrier *Tanais Dream*, on a set path through the IS applying all rules and regulations until the simulation was terminated. The expertise of Participant 2 (P2) have already been outlined; the expertise of the remaining participants is as follows:

Participants 3 (P3), 4 (P4) and 5 (P5) are all cadets in the middle of their BSc(hons) in Nautical Science and are working towards "*Certification for Officers in charge of a Navigational Watch (OOW) unlimited, STCW Convention regulation II/1*". They all have at least 12 months of sea time. P2 and P5 were paired together and P3 and P4 were paired together.

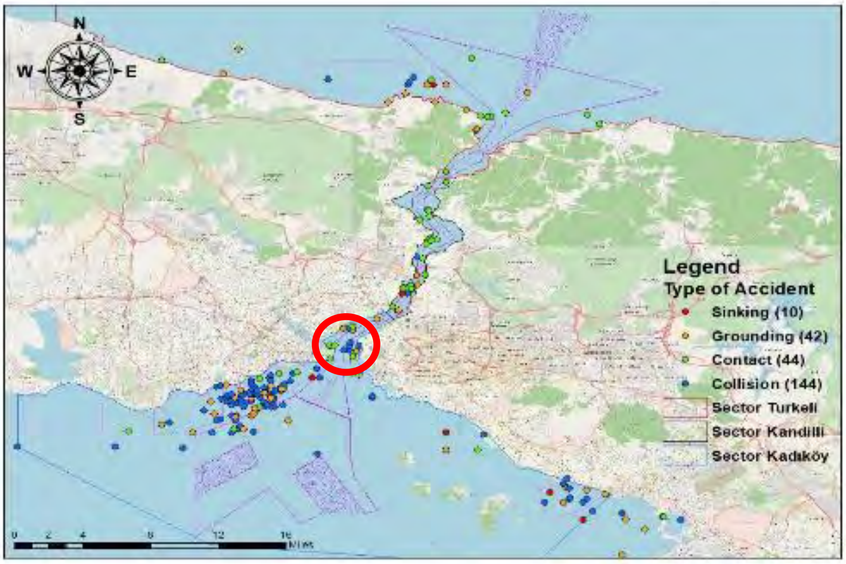


Figure 33. Location of the Tanais Dream and Sultanahmet collision in the Kadikoy VTS region

6.2.1 *Collision Scenario 1*

In the first scenario of the collision simulation, P3 and P4 were assigned to Bridge 1 as OOW and Lookout respectively. P2 and P5 were assigned to Bridge 2 as OOW and Lookout respectively. In order to maintain conditions as close to the accident as possible, both bridge teams were not told that it was a collision scenario. All they had to do was navigate the Bulk Carrier through a passage of the IS until the simulation terminated. Clear instructions were made that they must obey the rules of the TSS and COLREGS and take any actions to avoid collisions or groundings were necessary. Both teams began the simulation further up the strait from the collision incident as shown by Figure 34.

Figure 34. Starting location of the vessel in the collision simulation.

Towards the end of the planned route, the RO-RO ferry would depart from Harem Pier at 19:32, the time stated in the accident report. The ferry would be on an automated track to follow the route taken in the accident report at the stated speed of approximately 9 knots. The Bulk Carrier was set to be travelling at 11.5 knots. Both bridge teams followed the planned route within the TSS and obeyed all rules, however there was a completely different situation in each bridge once the ferry was within a few cables.

- Bridge 1 Team (P3 OOW and P4 Lookout) – this team followed the route precisely until the scenario terminated. This team had the advantage of the 360^{O} view out of the “windows”. What was apparent was the bridge team did not track the ferry once it was crossing the TSS. It was not until the ferry was within less than 2 cables that the lookout spotted the ferry out of the port side “window”. At which point it was too late and the ferry collided with the stern of the Bulk Carrier at a similar time as stated in the real accident report. It was noted after the simulation that the lookout felt confident enough in their ability with the added advantage of the “windows”, and thus did not track the ferry once it was in the TSS.
- Bridge 2 Team (P2 OOW and P5 Lookout) – this team also followed the route until the scenario terminated. However, they made turns further up the strait at slightly different intervals than stated in the accident report. Similarly, they also did not track the ferry as it crossed the TSS, yet they did not have a collision. The ferry passed to the stern of the Bulk Carrier. This was an interesting outcome as the team did not have the option of port and starboard windows to see the ferry incoming, nor did the team track the ferry using the radar. It seems that given a slightly different voyage through the straight, the collision would not occur.

6.2.2 Collision Scenario 2

In the second scenario the teams swapped bridges to provide a fair reflection of the test and also swapped rolls within their respective bridge teams. The rules applied as with the first scenario; however, they were told to expect something slightly different. An additional recreational yacht was added to depart Eminönü (Turyol) ferry terminal purely as a distraction and not as an additional collision incident. Similarly, lookouts were told to only report lights to the OOW with no additional information.

- Bridge 1 Team (P2 Lookout and P5 OOW) – again the planned route was followed precisely and resulted in a collision. However, this time it was the Bulk-Carrier that collided with the ferry directly into the ferry's starboard side. Again, it was the team on Bridge 1 that collided with the ferry. This again led to the idea that having the ability to see out of the "windows" with 360^{O} vision gave the team a false sense of securely in that they didn't track the ferry and chose to look out of the windows.

- Bridge 2 Team (P3 Lookout and P4 OOW) – this team again followed the planned route was followed precisely but this time they tracked the ferry and took evasive action. In this regard they followed the rules of COLREG to a certain degree. They obeyed rules 5, 7, 8, and 16 and partially obey rule 10. The definitions of these can be found in Appendix 1. The collision was avoided by turning to starboard and providing maintaining safe distance to avoid the ferry. Similarly, it was clearly apparent that the team were taking evasive action. However, they were in breach of Rule 10 whereby they left the TSS to avoid the collision but did not exit at as close to right angles as possible.

This simulation replicated, as close as possible, the situation that the captain of the ferry did not see the Bulk Carrier in time and thus could not avoid the collision. Similarly, the Bulk Carrier could not have avoided collision without breaking Rule 10 of COLREG. This simulation has shown that given the poor lookout on the ferry and the potential consequences that followed, to avoid the collision, the Bulk Carrier had to leave the TSS.

7 Conclusions

This research aimed to assist with navigational safety within the EC and IS by investigating marine accidents and identifying the high-risk areas in terms of grounding and collision-contact for the DS and IS. The aim of this project was accomplished through the following objectives:

- O1: Investigate marine accidents and develop an accident risk map and database for the DS and IS.

  This objective was achieved through the review of accident reports in the DS and IS associated with groundings, collision/contacts and sinkings. A database of accidents was developed from multiple sources. These accidents were assessed through Spatial Analysis using the Kernel Density function to pinpoint where these accidents occurred. From here the risk maps of the DS and Is were developed. It was found that the DS was a relatively low risk waterway, while the IS was a very congested waterway in terms of accidents. Furthermore, the accident reports were further analyzed using the HFACS approach to determine the factors that cause these grounding and collision/contact accidents. It was determined that grounding accidents are linked to the practices and the conduct of the bridge team in the preconditions of accidents. These were, Substandard Practices of Team Members, Decision Based Errors, and Perceptual Errors. It can be seen that collision/contact accidents are more complicated in their accident formation. One example is a combination of harsh weather conditions and technological problems (such as electronic navigation failure), or lack of awareness from the watch team and failure to follow procedure/incorrect company procedure. This objective is fulfilled in Sections 2 and 3.

- O2: Identify and evaluate the suitability existing Risk Control Measures (RCMs) that apply to narrow waterways.

  This objective was achieved through the development of the HFACS results into a Dynamic Risk Assessment Model using BNs. A risk model for both the DS and IS were developed and the model was tested using case studies of a grounding accident and a collision accident in the IS. The model identified that with commonly known information regarding operational conditions and organizational influences, the accident could have potentially been avoided. However, once further information regarding the condition of the vessels and the practices of the crew were revealed (post-accident), the risk of collision and grounding increased. This is particularly true regarding the collision accident case study whereby if the condition of the crew, the passage planning and the ergonomics of the Ro-Ro ferry were known, the collision should have been avoided. This dynamic model then provided the basis to highlight and rank RCMs to improve safety in narrow waterways. The top ranked RCM was passage and anchorage with a pilot (0.65) (Measure 3), with the next highest RCM being Using the Dynamic Risk Assessment Model (Measure 6) (0.53) developed in this research. Thus, the outcomes of the risk model were teste din the Bridge simulator. This objective is achieved in Sections 4 and 5

- O3: Prepare navigation safety guidelines and test their feasibility in a bridge simulator.

  Finally, this objective was fulfilled by testing the results of the case studies using dynamic risk model in a bridge simulator. Two simulations were built to replicate the accident operational conditions: one grounding and on collision. The results showed that the grounding could have been avoided on a very similar passage if the charts on the vessel had been updated. Similarly, the simulation of the collision scenario showed that given the behavior of the bridge team on the ferry, the best possible way for the Bulk Carrier to avoid the collision was to obey COLREGS but partially violate rule 10 by leaving the TSS. This objective is fulfilled in Section 6.

References

[1] Kujala P., Hanninen M., Arola T., and Ylittalo J., “Analysis of the marine traffic safety in the Gulf of Finland”, *Reliability Engineering & System Safety*, Vol 94, (2009). pp.1349-1357.

[2] Montewka J., Goerlandt F. & Kujala P., “Determination of collision criteria and causation factors appropriate to a model for estimating the probability of maritime accidents.” *Ocean Engineering,* 40, (2012). pp.50-61.

[3] Chauvin C., Lardjane S., Morel G., Clostermann J. P. and Langard B,. “Human and organizational factors in maritime accidents: analysis of collisions at sea using the HFACS”. *Accident Analysis & Prevention*, Vol 59, (2013), pp.26-37.

[4] Uğurlu Ö, Köse E, Yıldırım U, and Yüksekyıldız E. “Marine accident analysis for collision and grounding in oil tanker using FTA method”, *Maritime Policy & Management*, Vol 42, (2015), pp.163-85. https://doi.org/10.1080/03088839.2013.856524

[5] Uğurlu, Ö., Nişancı, R., Köse, E., Yıldırım, U., and Yüksekyıldız, E., “Investigation of oil tanker accidents by using GIS”, *International Journal of Maritime Engineering*, Vol 157, No. 2, (2015) pp.113-124.

[6] Yilidirim U., Uğurlu Ö. ,Basar E. and Yuksekyildiz E., “Human factor analysis of container vessel’s grounding accidents”, *International Journal of Maritime Engineering*, Vol 159, (2017), pp.89-98.

[7] Mullai A. and Paulsson U., “A grounded theory model for analysis of marine accidents”, *Accident Analysis & Prevention*, Vol 43, (2011), pp.1590-1603.

[8] Uğurlu, Ö., Yıldırım, U., Başar, E., “Analysis of Grounding Accidents Caused by Human Error”, *Journal of Marine Science and Technology* Vol. 23, No.5, (2015), pp.748-760.

[9] MAIB, “Marine Accident Investigation Branch Annual Report 2017”, (2018) Available at: https://www.gov.uk/government/publications/maib-annual-report-2017

[10] Bateman, S., Ho, J., and Mathai, M.,. “Shipping patterns in the Malacca and Singapore straits: an assessment of the risks to different types of vessel”, *Contemporary Southeast Asia*, (2007), pp.309-332.

[11] Huang, D.-Z., Hu, H. and Li, Y.-Z., “Spatial analysis of maritime accidents using the geographic information system”, *Transportation Research Record* Vol. 2326, No. 1, (2013), pp.39-44.

[12] Squire, D., “The Hazards of Navigating The Dover Strait (Pas-de-Calais) Traffic Separation Scheme”, *Journal of Navigation,* Vol. 56, No. 2, (2003) pp.195-210.

[13] Uğurlu, Ö. and Yıldız, S., “Evaluation of Passenger Vessel Accidents and Spatial Analysis”, *Journal of ETA Maritime Science* Vol. 4, No. 4, (2016), pp.289-302.

[14] Ulusçu, Ö.S., Özbaş, B., Altıok, T. and Or, İ.,. “Risk Analysis of the Vessel Traffic in the Strait of Istanbul”, *Risk Analysis*, Vol. 29, No. 10, (2009) pp.1454-1472.

[15] Akhtar, M.J. and Utne, I.B., “Human fatigue's effect on the risk of maritime groundings – A Bayesian Network modeling approach”, *Safety science*, Vol. 62, (2014), pp.427-440.

[16] Macrae, C., “Human factors at sea: common patterns of error in groundings and collisions”, *Maritime Policy & Management*, Vol. 36, No. 1, (2009), pp.21-38.

[17] Uğurlu, Ö., Kum, S. and Aydoğdu, Y.V., “Analysis of occupational accidents encountered by deck cadets in maritime transportation”, *Maritime Policy & Management*, (2016) pp.1-19.

[18] Schröder-Hinrichs, J.-U., Hollnagel, E. and Baldauf, M., “From Titanic to Costa Concordia—a century of lessons not learned”, *WMU Journal of Maritime Affairs*, Vol. 11, No. 2, (2012) pp.151-167.

[19] Uğurlu, Ö., Yıldız, S., Loughney, S., Wang, J., Kuntchulia, S. and Sharabidze, I., “Analyzing Collision, Grounding, and Sinking Accidents Occurring in the Black Sea Utilizing HFACS and Bayesian Networks”, *Risk Analysis*, Vol. 40, No. 12, (2020), pp.2610-2638.

[20] Praetorius, G. and Hollnagel, E., “Control and resilience within the maritime traffic management domain”, *Journal of Cognitive Engineering and Decision Making* Vol. 8, No. 4, (2014), pp.303-317.

[21] van Westrenen, F. and Praetorius, G., “Maritime traffic management: a need for central coordination?”, *Cognition, Technology & Work*, Vol. 16, No. 1, (2014), pp. 59-70.

[22] Başar, E., “Investigation into marine traffic and a risky area in the Turkish Straits system: Canakkale Strait”, *Transport*, Vol. 25, No. 1, (2010), pp.5-10.

[23] Köse, E., Başar, E., Demirci, E., Güneroğlu, A. and Erkebay, Ş., “Simulation of marine traffic in Istanbul Strait”, *Simulation Modelling Practice and Theory*, Vol. 11, No. 7, (2003), pp.597-608.

[24] Ugurlu, O., Yıldırım, U., and Yuksekyıldız, E., “Marine Accident Analysis with GIS”, *Journal of Shipping and Ocean Engineering*, Vol. 3, (2013), pp.21-29.

[25] Yildiz, S., Sönmez, V.Z., Uğurlu, Ö., Sivri, N., Loughney, S., and Wang, J., “Modelling of possible tanker accident oil spills in the Istanbul Strait in order to demonstrate the dispersion and toxic effects of oil pollution”, *Environmental Monitoring and Assessment*, Vol. 193, No. 8, (2021), pp.1-19.

[26] Aydogdu, Y.V., Yurtoren, C., Park, J.-S. and Park, Y.-S., “A study on local traffic management to improve marine traffic safety in the Istanbul Strait”, *The Journal of Navigation*, Vol. 65, No. 1, (2012) pp.99-112.

[27] Emecen Kara, E.G., “Risk Assessment in the Istanbul Strait Using Black Sea MOU Port State Control Inspections”, *Sustainability*, Vol. 8, No. 4, (2016), pp. 390.

[28] UAB, “Türk Boğazları Gemi Geçiş Istatistikleri.”, (2021), Accessed February 01, 2020. https://denizcilikistatistikleri.uab.gov.tr/ turk-bogazlari-gemi-gecis-istatistikleri

[29] Qu, X., Meng, Q., and Li, S., “Analyses and implications of accidents in Singapore Strait”, *Transportation Research Record,* Vol. 2273, No. 1, (2012), pp.106-111.

[30] Graziano, A., Teixeira, A., and Soares, C.G., “Classification of human errors in grounding and collision accidents using the TRACEr taxonomy”, *Safety science*, Vol. 86, 2016, pp.245-257.

[31] Martins, M.R., and Maturana, M.C., “Human error contribution in collision and grounding of oil tankers”, *Risk Analysis*, Vol. 30, No. 4, (2010), pp.674-698.

[32] Yıldırım, U., Başar, E., and Uğurlu, Ö., “Assessment of collisions and grounding accidents with human factors analysis and classification system (HFACS) and statistical methods”, *Safety Science,* Vol. 119, (2019), pp. 412-425.

[33] Akten, N., “Analysis of shipping casualties in the Bosphorus”, *The Journal of Navigation*, Vol. 57, No. 3, (2004), pp.45-356.

[34] Arslan, O. and Turan, O., “Analytical investigation of marine casualties at the Strait of Istanbul with SWOT–AHP method”, *Maritime Policy & Management*, Vol. 36, No. 2, (2009), pp.131-145.

[35] Aydogdu, Y.V., “A comparison of maritime risk perception and accident statistics in the

Istanbul Straight”, *The Journal of Navigation*, Vol. 67, No. 1, (2014), pp.129-144.

[36] Roberts, S.E., “Fatal work-related accidents in UK merchant shipping from 1919 to 2005”, *Occupational medicine*, Vol. 58, No. 2, (2008), pp.129-137.

[37] Malta, T., “Marine Safety Investigation Report”, (2019), Accessed March 03, 2020. https://mtip.gov.mt/en/Pages/MSIU/Marine-Safety-Investigation-Unit.aspx

[38] ECON, “Türk Boğazlarında Yaşanan Denizcilik Kazaları”, (2019), Accessed May 10, 2019. http://econ318-eay2.bilkent.edu.tr/kazalar.

[39] Anon, “United Kingdom: Huayang Endeavour and Seafrontier report” published, Asia News Monitor, (2018) Asia News Monitor, 2018–04-27.

[40] Apostol-Mates, R. & Barbu, A.. Fatigue leading to human error: a study based on marine accidents. *Scientific Bulletin ("Mircea cel Bătrân" Naval Academy)*, Vol. 22, No. 2, (2019) pp.110–115.

[41] Maglić, L., Valčić S., Gundić S. and Maglic, L. “Voice Communication Systems Impact on Navigating Officers.”, *Journal of marine science and engineering*, Vol. 8, No. 3, (2020), p.197.

[42] Othman, M. K., Fadzil, M. N. and Abdul Rahman, N. S. F., “The Malaysian Seafarers Psychological Distraction Assessment Using a TOPSIS Method”, *International journal of e-navigation and maritime economy*, Vol. 3, (2015), pp.40–50.

[43] Maglić, Lovro, Zec, Damir, Frančić and Vlado, “Model of the Adaptive Information System on a Navigational Bridge”, *Journal of Navigation*, Vol. 69, No. 6, (2016), pp.1247– 1260.

[44] Tsimplis M. & Papadas S., “Information Technology in Navigation: Problems in Legal Implementation and Liability”. *Journal of Navigation*, Vol. 72, No. 4, (2019), pp.833– 849.

[45] Turna İ. and Öztürk O. B., “A causative analysis on ECDIS-related grounding accidents”. *Ships and offshore structures*, Vol. 15, No. 8, (2020). pp.792–803.

[46] Tabri, K., Broekhuijsen J., Matusiak J. and Varsta P., “Analytical modelling of ship collision based on full-scale experiments.”, *Marine structures*, Vol. 22, No. 1, (2009), pp.42–61.

[47] Silva, J.E, Garbatov, Y & Guedes Soares, C, “Reliability assessment of a steel plate subjected to distributed and localized corrosion wastage.”, *Engineering structures*, Vol. 59, (2014), pp.13–20.

[48] IMO, “STCW Convention and Code Including 2010 Manila Amendments”, *International Maritime Organization*, (2011), London, UK.

[49] IMO “International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW)”, (2022) Adoption: 7 July 1978; Entry into force: 28 April 1984; Major revisions in 1995 and 2010. [available at: https://www.imo.org/en/OurWork/HumanElement/Pages/STCW-Conv-LINK.aspx]

[50] MAIB, “Report on the investigation into the listing, flooding and grounding of Hoegh Osaka Bramble Bank”, (2016). The Solent, UK on 3 January 2015. *Marine Accident Investigation Branch, REPORT NO 6/2016*.

[51] Praetorius, G., Kataria, A., Petersen, E.S., Schröder-Hinrichs, J.U., Baldauf, M. and Kähler, N., “Increased awareness for maritime human factors through e-learning in crew-centered design.”, *Procedia Manufacturing*, Vol. 3, (2015), pp.2824-2831.

[52] de Vries, L., “Work as done? Understanding the practice of sociotechnical work in the maritime domain.” *Journal of Cognitive Engineering and Decision Making*, Vol. 11, No. 3, (2017), pp.270-295.

[53] DTGM. 2017. Turkish Straits ship transition statistics. Ankara/Turkey. Available at: https://atlantis.udhb.gov.tr/istatistik/gemi_gecis.aspx

[54] MCA, "Safer Navigation in the Dover strait", (2010), Available at: https://web.archive.org/web/20100828084218/http://www.mcga.gov.uk/c4mca/mcga07-home/emergencyresponse/mcga-searchandrescue/mcga-hmcgsar-sarsystem/channel_navigation_information_service__cnis_.htm

[55] Ayalew, L. and Yamagishi, H., "The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan.", *Geomorphology*, Vol. 65, No. 1, (2005), pp.15-31.

[56] Kavzoglu, T., Sahin, E.K. and Colkesen, I., " Landslide susceptibility mapping using GIS-based multi-criteria decision analysis, support vector machines, and logistic regression". *Landslides,* Vol. 11, No. 3, (2014), pp.425-439.

[57] Leidwanger, J., "Modeling distance with time in ancient Mediterranean seafaring: a GIS application for the interpretation of maritime connectivity.", *Journal of archaeological science*, Vol. 40, No. 8, (2013), pp.3302-3308.

[58] Erdogan, S., Yilmaz, I., Baybura, T. and Gullu, M., "Geographical information systems aided traffic accident analysis system case study: city of Afyonkarahisar". *Accident Analysis & Prevention*, Vol. 40, No. 1, (2008), pp.174-181.

[59] Liang, L.Y., Ma'soem, D.M. and Hua, L.T., "Traffic accident application using geographic information system.", *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 6, (2005), pp.3574-3589.

[60] Anderson, T.K., "Kernel density estimation and K-means clustering to profile road accident hotspots". *Accident Analysis & Prevention,* Vol. 41, No. 3, (2009), pp.359-364.

[61] Okabe, A., Satoh, T. and Sugihara, K., "A Kernel Density Estimation Method for Networks, its Computational Method And A GIS- Based Tool.", *International Journal of Geographical Information Science*, Vol. 23, No. 1, (2009), pp.7-32.

[62] IMO, "Global Integrated Shipping Information System: Marine Casualties and Incidents", *International Maritime Organization* (2020), Accessed August 08, 2020. https://gisis.imo.org/Public/MCI/Search.aspx.

[63] MAIB, "Marine Accident Investigation Branch reports", *Marine Accident Investigation Branch* (2020), Accessed March 12, 2020. https://www.gov.uk/maib-reports.

[64] UEİM, "Deniz Kazası İnceleme Raporu/ Marine Casualty Investigation Report" (No.29/DNZ04/2020). (2021), Available at: https://ulasimemniyeti.uab.gov.tr/uploads/pages/deniz/meds un-rapor.pdf (accessed 14.12.2020

[65] OpenCPN, "Find the charts you need", (2020) Accessed February 05, 2020. https:// opencpn.org/OpenCPN/info/chartsource.html.

[66] ESRI, "ArcMap 10.5 Computer Software", (2017), Accessed May 05, 2019. https://desktop.arcgis .com/ en/arcmap/.

[67] Bonnier, A., Finné, M. and Weiberg, E., "Examining land-use through GIS-Based kernel density estimation: a Re-Evaluation of legacy data from the berbati-limnes survey", *Journal of Field Archaeology*, Vol. 44, No. 2, (2019), pp.70-83

[68] Prasannakumar, V., Vijith, H., Charutha, R. and Geetha, N., "Spatio-temporal clustering of road accidents: GIS based analysis and assessment", *Procedia-Social and Behavioral Sciences*, Vol. 21, (2011), pp.317-325.

[69] Xie, Z. and Yan, J., “Kernel Density Estimation of Traffic Accidents in A Network Space”, *Computers, Environment and Urban Systems*, Vol. 32, No. 5, (2008), pp.396-406.

[70] Tehrany, M.S., Pradhan, B., Mansor, S. and Ahmad, N., “Flood Susceptibility Assessment Using GIS-Based Support Vector Machine Model With Different Kernel Types”, *Catena*, Vol. 125, (2015), pp.91-101.

[71] Sandhu, H., Singh, G., Sisodia, M. and Chauhan, R., “Identification of Black Spots on Highway with Kernel Density Estimation Method”, *Journal of the Indian Society of Remote Sensing*, Vol. 44, No. 3, (2016), pp.457-464.

[72] Gatrell, A.C., Bailey, T.C., Diggle, P.J. and Rowlingson, B.S., “Spatial Point Pattern Analysis and its Application in Geographical Epidemiology”, *Transactions of The Institute of British Geographers*, Vol. 21, No. 1, (1996), pp.256-274.

[73] Exchange, “How does changing the kernel density search radius affect the units expressed in the map legend?.”, *GIS Stack Exchange*. (2021), Accessed February 24, 2021. https://gis.stackex change.com/questions/62627/howdoes-changing-the-kernel-density-search-radius-affect-the-units-expressed-in?noredirect=1&lq=1.

[74] [Yildiz, S., Uğurlu, Ö., Wang, J. and Loughney, S., “Application of the HFACS-PV approach for identification of human and organizational factors (HOFs) influencing marine accidents.”, *Reliability Engineering & System Safety*, Vol. 208, (2021), pp.107395

[75] Uğurlu, Ö., Yıldız, S., Loughney, S. and Wang, J., “Modified human factor analysis and classification system for passenger vessel accidents (HFACS-PV)”, *Ocean Engineering*, Vol. 161, (2018), pp.47-61.

[76] Uğurlu, F., Yıldız, S., Boran, M., Uğurlu, Ö. and Wang, J., “Analysis of fishing vessel accidents with Bayesian network and Chi-square methods”, *Ocean Engineering*, Vol.198, 2020, pp.106956.

[77] Güngör, M. and Bulut, Y., “On the Chi-Square Test”. *Doğu Anadolu Bölgesi Araştırmaları,* Vol. 7, No. 1, (2008), pp.84-89.

[78] McHugh, M.L., “The chi-square test of independence”, *Biochemia medica*, Vol. 23, No. 2, (2013), pp.143-149.

[79] Franke, T.M., Ho, T. and Christie, C.A., “The chi-square test: Often used and more often misinterpreted.”, *American Journal of Evaluation,* Vol. 33, No. 3, (2012), pp.448-458.

[80] Qu, X., Meng, Q. and Suyi, L., “Ship collision risk assessment for the Singapore Strait.”, *Accident Analysis & Prevention*, Vol. 43, No. 6, (2011), pp.2030-2036.

[81] Wang, H., Liu, Z., Wang, X., Graham, T. and Wang, J., “An analysis of factors affecting the severity of marine accidents.”, *Reliability Engineering & System Safety*, Vol. 210, (2021), pp.107513.

[82] Istikbal, C., “Turkish Straits: Difficulties and the importance of pilotage. Turkish Straits-Maritime Safety, Legal and Environmental Aspects”, *Turkish Marine Research Foundation*, (2006), İstanbul, Turkey.

[83] Erol, S., Demir, M., Çetisli, B. and Eyüboglu, E., “Analysis of ship accidents in the Istanbul Strait using neuro-fuzzy and genetically optimised fuzzy classifiers”, *The Journal of Navigation*, Vol. 71, No. 2, (2018), pp.419.

[84] Nævestad, T.O., Phillips, R.O., Størkersen, K.V., Laiou, A. and Yannis, G., “Safety culture in maritime transport in Norway and Greece: Exploring national, sectorial and organizational influences on unsafe behaviours and work accidents”, *Marine Policy*, Vol. 99, (2019), pp.1-13.

[85] MCA, “Guidance Dover Strait crossings: channel navigation information service (CNIS)”, *Maritime Coastguard Agency* (2014) Accessed December 22, 2021. https://www.gov.uk/government/publications/dover-strait-crossings-channel-navigation-information-service/dover-strait-crossings-channel-navigation-information-service-cnis.

[86] Wiegmann DA. and Shappell SA. “Human factors analysis of postaccident data: Applying theoretical taxonomies of human error.”, *The International Journal of Aviation Psychology*. Vol. 7, (1997), pp.67-81. https://doi.org/10.1207/s15327108ijap0701_4

[87] Chauvin C., Lardjane S., Morel G., Clostermann J. P. and Langard B,. “Human and organizational factors in maritime accidents: analysis of collisions at sea using the HFACS”. *Accident Analysis & Prevention*, Vol 59, (2013), pp.26-37.

[88] Akhtar MJ, and Utne IB. “Human fatigue’s effect on the risk of maritime groundings – A Bayesian Network modeling approach”, *Safety Science*, Vol. 62, (2014), pp.427-40. https://doi.org/10.1016/j.ssci.2013.10.002

[89] Shappell S, and Wiegmann D., “HFACS Analysis of Military and Civilian Aviation Accidents: A North American Comparison”, *Proceedings of the Annual Meeting of the International Society of Air Safety Investigators (ISASI) Forum*, Gold Coast, Australia, (2004) pp.1-8.

[90] Shappel SA, and Wiegmann DA., “The Human Factors Analysis and Classification System-HFACS.”, *US Federal Aviation Administration*; Illinois, United States, (2000), pp. 1-19.

[91] Tvaryanas AP, Thompson WT. and Constable SH., “Human factors in remotely piloted aircraft operations: HFACS analysis of 221 mishaps over 10 years”, *Aviation, space, and environmental medicine*, Vo. 77, (2006), pp.724-32.

[92] Theophilus SC, Esenowo VN, Arewa AO, Ifelebuegu AO, Nnadi EO, and Mbanaso FU. “Human factors analysis and classification system for the oil and gas industry (HFACS-OGI)”, *Reliability Engineering & System Safety*, Vol. 167, (2017) pp.168-76. https://doi.org/10.1016/j.ress.2017.05.036

[93] Zhang M, Zhang D, Goerlandt F, Yan X, and Kujala P., “Use of HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters”, *Safety Science,* Vol. 111, (2019), pp.128-43. https://doi.org/10.1016/j.ssci.2018.07.002

[94] Schröder-Hinrichs JU, Baldauf M, and Ghirxi KT., “Accident investigation reporting deficiencies related to organizational factors in machinery space fires and explosions”, *Accident Analysis and Prevention*, Vol. 43, (2011), pp.1187-96. https://doi.org/10.1016/j.aap.2010.12.033

[95] Patterson JM, and Shappell SA., “Operator error and system deficiencies: analysis of 508 mining incidents and accidents from Queensland, Australia using HFACS”, *Accident Analysis and prevention*, Vol. 42, (2010), pp.1379-85. https://doi.org/10.1016/j.aap.2010.02.018

[96] Zhan Q, Zheng W, and Zhao B., “A hybrid human and organizational analysis method for railway accidents based on HFACS-Railway Accidents (HFACS-RAs)”, *Safety Science*, Vol. 91, (2017), pp.232-50. https://doi.org/10.1016/j.ssci.2016.08.017

[97] Li WC, Head T, Wu FE, Chen SY, and Yu CS., “The investigation of decision errors in aviation mishaps by applying the human factors analysis and classification system (HFACS)”, *Human Performance, Situation Awareness and Automation: Current Research and Trends*, Vol 1. (2004), pp.283-9.

[98] Rashid HSJ, Place CS, and Braithwaite GR., “Helicopter maintenance error analysis: Beyond the third order of the HFACS-ME”, *International Journal of Industrial Ergonomics*, Vol. 40, (2010), pp.636-647. https://doi.org/10.1016/j.ergon.2010.04.005

[99] Olsen NS., “Coding ATC incident data using HFACS: Inter-coder consensus”, *Safety Science,* Vol. 49, (2011), pp.365-70. https://doi.org/10.1016/j.ssci.2011.05.007

[100] IMO, “Amendments to the Code for the Investigation of Marine Casualties and Incidents (Resolution A.849(20)). In: Organization IM, editor. A884(21)”, *International Maritime Organization*, (1999), pp. 1-42.

[101] Ergai A, Cohen T, Sharp J, Wiegmann D, Gramopadhye A, and Shappell S, “Assessment of the Human Factors Analysis and Classification System (HFACS): Intra-rater and inter-rater reliability”, *Safety Science*, Vol. 82 (2016), pp.393-398. https://doi.org/10.1016/j.ssci.2015.09.028

[102] Chen ST, and Chou YH., “Examining Human Factors for Marine Casualties using HFACS - Maritime Accidents (HFACS-MA)”, *12th International Conference on Its Telecommunications (ITST-2012)*, (2012), pp.385-90. https://doi.org/10.1109/ITST.2012.6425205

[103] Xi YT, Fang QG, Chen WJ, and Hu SP., “Case-based HFACS for Collecting, Classifying and Analyzing Human Errors in Marine Accidents”, *International Conference on Industrial Engineering and Engineering Management*. (2009), pp.2148-2153. https://doi.org/10.1109/IEEM.2009.5373128

[104] Xi Y, Chen W, Fang Q, and Hu S., “HFACS model-based data mining of human factors-a marine study”, *Industrial Engineering and Engineering Management (IEEM), 2010 IEEE International Conference on: IEEE*, (2010), pp.1499-1504. https://ieeexplore.ieee.org/document/5674153/

[105] Wiegmann D, Boquet A, Detwiler C, Holcomb K, and Shappell S., “Human Error and General Aviation Accidents : A Comprehensive, Fine-grained Analysis Using HFACS”, *Federal Aviation Administration*, Washington, United States, (2005) pp. 1-24.

[106] Chen ST, Wall A, Davies P, Yang ZL, Wang J, and Chou YH., “A Human and Organisational Factors (HOFs) analysis method for marine casualties using HFACS-Maritime Accidents (HFACS-MA)”, *Safety Science*, Vol. 60, (2013), pp.105-114. https://doi.org/10.1016/j.ssci.2013.06.009

[107] Celik M, and Cebi S., “Analytical HFACS for investigating human errors in shipping accidents”, *Accident Analysis and Prevention*, Vol. 41, (2009), pp.66-75.

[108] Han DF, and Ding S., “Review of human factors in maritime system”, *Applied Mechanics and Materials. Switzerland*, (2013), pp.679-682. https://doi.org/10.4028/www.scientific.net/AMM.397-400.679

[109] Uğurlu Ö, Yıldız S, Loughney S, Wang J, Kuntchulia S, and Sharabidze I., “Analysing of Collision, Grounding and Sinking Accident Occurring in the Black Sea Utilizing GIS, HFACS and Bayesian Networks”, *Risk Analysis*, (2020), pp.1-14. https://doi.org/10.1111/risa.13568

[110] Mazaheri A, Montewka J, and Kujala P., “Towards an evidence-based probabilistic risk model for ship-grounding accidents”, *Safety Science*, Vol. 86, (2016), pp.195-210. https://doi.org/10.1016/j.ssci.2016.03.002

[111] Graziano A, Teixeira A, and Soares CG., “Classification of human errors in grounding and collision accidents using the TRACE taxonomy”, *Safety Science*, Vol. 86, (2016), pp.245-57. https://doi.org/10.1016/j.ssci.2016.02.026

[112] Hetherington C, Flin R, and Mearns K., “Safety in shipping: The human element”, *Journal of safety research*, Vol. 37, (2006), pp.401-11. https://doi.org/10.1016/j.jsr.2006.04.007

[113] Tzannatos E., “Human element and accidents in Greek shipping”, *Journal of Navigation*. Vol.

63, (2010), pp.1-9. https://doi:10.1017/S0373463309990312

[114] Rothblum AM., "Human error and marine safety", *National Safety Council Congress and Expo*, Orlando, United States, (2000), pp. 7-18.

[115] Pietrzykowski Z, Wielgosz M, and Breitsprecher M., "Navigators' Behavior Analysis Using Data Mining", *Journal of Marine Science and Engineering*, Vol. 8, (2020), pp.50. https://doi.org/10.3390/jmse8010050

[116] Yoo Y, and Kim T-G., "An Improved Ship Collision Risk Evaluation Method for Korea Maritime Safety Audit Considering Traffic Flow Characteristics.", *Journal of Marine Science and Engineering*, Vol. 7, (2019), pp.448. https://doi.org/10.3390/jmse7120448

[117] Akyuz E., "A marine accident analysing model to evaluate potential operational causes in cargo ships", *Safety Science*, Vol.92, (2017), pp.17-25. https://doi.org/10.1016/j.ssci.2016.09.010

[118] Arslan V, Kurt RE, Turan O, De and Wolff L., "Safety Culture Assessment and Implementation Framework to Enhance Maritime Safety", *Transportation Research Procedia*, Vol. 14, (2016), pp.3895-904. https://doi.org/10.1016/j.trpro.2016.05.477

[119] Sætrevik B, and Hystad SW., "Situation awareness as a determinant for unsafe actions and subjective risk assessment on offshore attendant vessels" *Safety Science*, Vol. 93, (2017), pp.214-21. https://doi.org/10.1016/j.ssci.2016.12.012

[120] Uğurlu Ö., "Analysis of fire and explosion accidents occurring in tankers transporting hazardous cargoes", *Int J Ind Ergonom*, (2016), pp.1-20. https://doi.org/10.1016/j.ergon.2016.06.006

[121] Antão P, Almeida T, Jacinto C, and Guedes Soares C., "Causes of occupational accidents in the fishing sector in Portugal", *Safety Science*, Vol. 46, (2008), pp.885-99. https://doi.org/10.1016/j.ssci.2007.11.007

[122] Khakzad, N., Khan, F., and Amyotte, P., "Safety analysis in process facilities: comparison of fault tree and Bayesian network approaches", *Reliability Engineering and System Safety*. Vol.96, (2011), pp.925-932.

[123] Yang X. and Mannan S., "The development and application of dynamic operational risk assessment in oil/gas and chemical process industry", *Reliability Engineering & System Safety*, Vol. 95 No. 7, (2010), pp. 806-815, https://doi.org/10.1016/j.ress.2010.03.002.

[124] Eleye-Datubo, A., Wall, A., Saajedi, A. and Wang, J., "Enabling a powerful marine and offshore decision-support solution through Bayesian network technique", *Risk Analysis,* Vol. 26**,** (2006), pp.695-721.

[125] Abimdola, M., Khan, F. and Khakzad, N., "Dynamic safety risk analysis of offshore drilling", *Journal of Loss Prevention in Process Industries*, Vol. 30, (2014), pp. 74-85.

[126] Liu, R., Hasan, A. R., Ahluwalia, A. and Mannan, S. M., "Well specific oil discharge risk assessment by a dynamic blowout simulation tool", *Process Safety and Environmental Protection*, Vol. 103, (2016), pp. 183-191.

[127] Cai, B., Liu, Y., Liu, Z., Tian, X., Zhang, Y. and Ji, R., "Application of Bayesian networks in quantitative risk assessment of subsea blowout preventer operations", *Risk Analysis,* Vol. 33, No. 7, (2013), pp.1293-1311.

[128] Jones, B., Jenkinson, I., Yang, Z. and Wang, J., "The use of Bayesian network modelling for maintenance planning in a manufacturing industry", *Reliability Engineering and System Safety*, Vol. 95, No. (3), (2010), pp.267-277.

[129] Wu, S. Zhang, L., Zheng, W., Liu, Y., and Lundteigen, M. A., "A DBN-based risk assessment

model for prediction and diagnosis of offshore drilling incidents", *Journal of Natural Gas Science and Engineering*, Vol. 34, pp.139 - 158

[130] Loughney S, and Wang J., "Bayesian network modelling of an offshore electrical generation system for applications within an asset integrity case for normally unattended offshore installations". *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*. Vol. 232, No. 4, (2018), pp.402-420. doi:10.1177/1475090217704787

[131] Loughney S, Wang J, and Matellini D., "Utilising Bayesian networks to demonstrate the potential consequences of a fuel gas release from an offshore gas-driven turbine", *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, Vol. 233, No. 4, (2019), pp.1177-1197. doi:10.1177/1475090218816218

[132] Bolstad, W., M. "*Introduction to Bayesian Statistics", 2nd edition. John Wiley & Sons. (2007).

[133] Yeo, C., Bhandari, J., Abbassi, R., Garaniva, V., Chai, S. and Shomali, B. "Dynamic risk analysis of offloading process in floating liquefied natural gas (FLNG) platform using Bayesian Networks", *Journal of Loss Prevention in the Process Industries*, Vol. 41, (2016), pp.259-269.

[134] IMO, "Casualty Investigation Code: Code of the International Standards and Recommended Practices for a Safety Investigation into a Marine Casualty or Marine Incident", *International Maritime Organization,* (2008).

[135] MAIB, "Casualty Definitions used by the UK MAIB", *Marine Accident Investigation Branch*, (2013), United Kingdom.

[136] Bearfield, G. and Marsh, W., "Generalising Event Trees Using Bayesian Networks with a Case Study of Train Derailment", *International Conference on Computer Safety,* Berlin, Heidelberg (2005). pp. 52-66.

[137] Hänninen, M., "Analysis of human and organizational factors in marine traffic risk modelling", *Helsinki University of Technology. Faculty of engineering and architecture. Department of applied mechanics* Espoo. (2008).

[138] Brooker, P., "Experts, Bayesian Belief Networks, rare events, and aviation risk estimates", *Safety Science,* Vol. 49**,** (2011), pp.1142-1155.

[139] Pristrom, S., Yang, Z., Wang, J. and Yan, X., "A novel flexible model for piracy and robbery assessment of merchant ship operations". *Reliability Engineering and System Safety,* Vol. 155**,** (2016), pp.196-211.

[140] Cai, B., Liu, Y., Fan, Q., Zhang, Y., Liu, Z., Yu, S., and Ji, R., "Multi-source information fusion-based fault diagnosis of ground-source heat pump using Bayesian network", *Applied Energy*, Vol. 114, (2014), pp.1-9.

[141] Fenton, N., and Neil, M., "*Risk Assessment and Decision Analysis with Bayesian Networks*". 1st edition. Taylor & Francis Group, London, UK: CRC Press. (2013).

[142] Matellini, D. B., Wall, A. D., Jenkinson, I. D., Wang, J. and Pritchard, R., "Modelling dwelling fire development and occupancy escape using Bayesian network", *Reliability Engineering and System Safety,* Vol. 114**,** (2013), pp.75-91.

[143] MAIB, "Report on the investigation of the grounding of British Enterprise Ahirkapi Anchorage Area Istanbul, Turkey on 11 December 2004", *Marine Accident Investigation Branch,* (2005), Report No 25/2005.

[144] EMSA, “Accident Investigation Report On The Collision Between TANAIS DREAM & SULTANAHMET Istanbul Strait / Sarayburnu 18th of December 2014”. *Republic of Turkey Ministry of Transport, Maritime Affairs and Communications Accident Investigation Board,* (2015) Report Number: 04/2015

[145] Yang, J. and Xu, D., “On the Evidential Reasoning Algorithm for Multiple Attribute Decision analysis Under Uncertainty”, *IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans,* Vol. 32, No. 3, (2002), pp.289 - 304.

[146] Ren, J., Jenkinson, I., Sii, HS., Wang, J., Xu, L. and Yang, JB., “An offshore safety assessment framework using fuzzy reasoning and evidential synthesis approaches”, *Journal of Marine Engineering and Technology,* Vol. 4, No.1, (2005), pp. 3 - 16.

[147] Loughney S., Wang J., Matellini DB. and Nguyen TT., “Utilizing the evidential reasoning approach to determine a suitable wireless sensor network orientation for asset integrity monitoring of an offshore gas turbine driven generator”, *Expert Systems with Applications*, Vol. 185, (2021), pp. 115583. https://doi.org/10.1016/j.eswa.2021.115583.

[148] Li, Y. and Liao, X., “Decision support for risk analysis on dynamic alliance”, *Decision support systems,* Vol. 42, (2007), pp.2043-2059.

[149] Yang, J., “Rule and Utility based evidential reasoning approach for multiattribute decision analysis under uncertainties”, *European Journal of operational Research,* Vol. 131, (2001), pp.31 - 61.

Appendix

Appendix 1 - International Regulations for Preventing Collisions at Sea (COLREG) applicable to Bridge simulator collision scenarios.

It is stipulated at Rule 5 Look-out of COLREG that "Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision."

It is stipulated at Rule 7 Risk of Collision of COLREG that "Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. If there is any doubt such risk shall be deemed to exist."

It is stipulated at Rule 8 Action to avoid Collision of COLREG that;

(a) Any action to avoid collision shall be taken in accordance with the Rules of this Part and shall, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship. (b) Any alteration of course and/or speed to avoid collision, shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar; a succession of small alterations of course and/or speed should be avoided. (c) If there is sufficient sea room, alteration of course alone may be the most effective action to avoid a close-quarters situation provided that it is made in good time, is substantial and does not result in another close-quarters situation. (d) Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance. The effectiveness of the action shall be carefully checked until the other vessel is finally past and clear. (e) If necessary to avoid collision or allow more to assess the situation, a vessel shall slacken her speed or take all way off by stopping or reversing her means of propulsion.

It is stipulated at Rule 10 Traffic Separation Schemes paragraph (c) of COLREG that "A vessel shall so far as practicable avoid crossing traffic lanes, but if obliged to do so shall cross on a heading as nearly as practicable at right angles to the general direction of traffic flow."

It is stipulated at Rule 16 Action by Give-way Vessel of COLREG that "Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear." and on the other hand at Rule 17 Action by Stand-on Vessel that; (a) (i) Where one of two vessels is to keep out of the way the other shall keep her course and speed. (ii) The latter vessel may however take action to avoid collision by her manoeuvre alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules. (b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision. (c) A power-driven vessel which takes action in a crossing situation in accordance with sub-paragraph (a) (ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side. (d) This Rule does not relieve the give-way vessel of her obligation to keep out of the way.

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ISBN No. 978-4-907408-41-1