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Identification of the Most Important Events to the Occurrence of a Disaster Using Maritime Examples

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Abstract: Previous studies on maritime disasters have noted the importance of searching for their causal factors in the analysis of different types of vessels and various regions where accidents have occurred. The main objective of the study that this article presents was to develop a new approach to modelling and causal analysis of the course of maritime disasters in order to provide a holistic evaluation of this phenomenon. The novel approach adopted to support the thesis combined event network analysis and fault tree analysis (used in functional analysis for modelling the structures of systems) in the process analysis. The authors advanced a thesis that, in the studied population of disasters, there were dominant classes of basic events in each phase of the process during the course of a disaster (distinguished by means of an event network). Thirty maritime disasters that occurred between 1912 and 2019 were selected for quantitative and qualitative analyses. In each disaster, the different phases of its course were distinguished: latent, initiating, escalating, critical, and energy release. A total of 608 basic events were identified in the population, enabling the identification and characterisation of 44 classes of events. The importance of the events in each of the phases was calculated by means of importance measures. The findings confirmed the thesis. At the same time, an analysis of the importance of basic events in each phase revealed that the most common basic events are not always the most important.

Keywords: accident causation; disaster at sea; event importance; fault tree analysis; event network analysis; cause and effect process modelling

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1. Introduction

Since the 1990s, the number of merchant marine vessels lost due to accidents has fallen significantly, which is remarkable considering that the merchant fleet has been steadily growing and today numbers more than 130,000 vessels, compared to 80,000 in the 1990s [1,2]. Meeting the challenges of maritime accident prevention is a credit to the long-term policies of international institutions on maritime transport safety, as well as shipowners and their investments in preventive measures [3,4]. Indeed, the consequences of maritime disasters are dramatic, with loss of life or limb or permanent injury, destruction of property, loss of cargo, destruction of the environment, and negative impacts on areas dependent on maritime transportation [5,6]. Disasters also generate high costs for rescue operations, disposal, and compensation.

However, since the second decade of the 21st century, maritime transport has faced an increasing number of new challenges that are changing the conditions for the practice of international shipping and affecting its safety [7]. Economic challenges are linked to the growing demand for maritime trade (according to an analysis, the demand will grow on average 2.1% per year between 2023 and 2027 [8,9]) and rising inflation due to the economic crisis associated with the COVID-19 pandemic and the war in Ukraine, which has affected global manufacturing, logistics. and supply chains. An ageing merchant fleet is not without its impact on the growing demand for maritime transport. Currently, the average age of a marine vessel is 21.9 years, and as for the type of vessel, the average age is 11.1 years for bulk carriers, 13.7 years for container ships, and 19.7 years of oil tankers [1]. The age of tankers, in particular, is a concern in the context of the increasing demand for oil and gas, the change in energy supply caused by the war in Ukraine, and the use of other shipping routes (which are more remote, costly, and generate more pollution).

At the same time, environmental regulations impose an obligation on maritime transport to reduce the negative impact of ships on the environment by, among other things, reducing exhaust emissions (i.e., CO_2, NO_x, or SO_x) [10,11], which is implemented through so-called slow sailing/steaming, use of alternative fuels [12] (i.e., LNG, methanol, ammonia, or electricity), and retrofitting ships with energy-efficient technologies [13–15] and exhaust cleaning systems [8]. In addition, maritime transport has to deal with the prevention of water pollution by oil spills and plastic [16–18], and ports must ensure access to low-emission energy supply infrastructure [19]. Decarbonisation policies are driving interest in new solutions and investment in green technologies, and this too will change maritime transportation. The growing popularity of electric cars (and the need to ship them) will be a challenge for marine transport, particularly in the context of vessel design, fire detection and fighting capabilities, and cargo loading procedures [1].

The introduced innovations run the risk of causing undesirable consequences and may reveal unknown weak links across a wide spectrum [20,21]. The decarbonisation of shipping directly increases the capacity and technical complexity of seagoing vessels, which may cause a return to serious accident risks involving such vessels.

A vessel is part of the global logistics chain for the delivery of goods, so maritime transportation is characterised by complex interactions among technology, human factors, organisations, and the environment [22]. New technologies introduced to the ship reduce the risk of human error bearing the main responsibility for a maritime accident—they are estimated at the level of 75% [1]—but increase the risk to the environment and the value of the ship [23] and cargo [24]. New technologies brought on board create new risks [25]. This is especially important with regard to the often inadequate training of crews [26]. The technologies used on today's ships and ocean-going facilities are evolving to either increase the scope of remote operator decision-making based on the data provided from the system or to eliminate it altogether and have the system make the decisions. The more complex a technical system, the more complex the course of its disaster becomes, and the greater the losses incurred [24,27,28]. The question arises whether universal factors occurring over the years, regardless of developing technologies and changing legal frameworks, are responsible for accidents that generally still happen. In the face of such conditions, understanding the development process and the course of a disaster at sea is desirable.

A number of papers [29–31] have emphasised that existing research in the field of accident causation in maritime transport is inadequate, especially compared to the scale of research conducted on road and air transport. The results from analysing specific types of vessels and selected regions of vessel operation have shown limited numbers and kinds of faults leading to the disasters [31,32]. The studies trying to combine technological, environmental, psychological, organisational, economic, and legal aspects during maritime disasters in a comprehensive way are insufficient [20]. In addition, the co-authors of a number of papers [29] have drawn attention to the quality of the results obtained—due to the fact that the research was performed for specific bodies of water or types of sea vessels, they are of limited applicability to other shipping regions and vessel types. Chen et al. [33] pointed out that there is a lack of scientific studies presenting the factors leading to maritime accidents in a more comprehensive and exhaustive manner, especially those that account for different types of vessels and various regions where accidents have occurred.

Persistent risks associated with ship operation (higher safety standards vs. the number, age, and size of ships) were the basis for the research and development of the method presented in this article. The authors of this paper were intrigued by whether a single event, or rather a combination of events of a certain type, is responsible for the course of a disaster at sea. In addition, the authors intended to identify the stages in the development of a disaster at sea, determine the importance of the events to the occurrence of these stages, as well as map the structure of the process of its progression.

This article presents a new approach to modelling and causal analysis of the course of disasters using maritime events as an example. The developed research method was used to confirm the thesis that, in the studied population of disasters, there were dominant classes of basic events in each phase of the process during the course of a disaster, which were distinguished by means of an event network. In practice, the method can be applied to improve the construction and procedures of existing and future technical systems in terms of improving their reliability and safety based on historical information processed in a statistical manner. The results of a study that attempts to answer these questions are also presented in this article.

2. Materials and Methods

2.1. Object of Analysis

In an effort to fill the research gap on the universal root causes of maritime disasters, without limiting ourselves to the types of ships or bodies of water, we selected 30 cases of disasters (Table 1) that occurred between 1912 and 2019.

Table 1. Population of maritime disasters selected for analysis.

Year	Unit Name	The Impact of the Disaster
1912	RMS Titanic	Ship capsizes and sinks, 1517 people die [34–38].
1914	RMS Empress of Ireland and SS Storsted	Shipwreck, death of 1012 people [39,40].
1915	SV Eastland	Ship capsizes, 844 people die [41].
1917	SV Mont Blanc and SS Imo	Loss of ships, deaths of about 2000 people, about 9000 injured, destruction of a city district [42,43].
1947	SV Ramdas	Ship capsizes and sinks, 669 people die [44,45].
1954	SF Tōya Maru	Ship capsizes and sinks, death of about 1170 people [46].
1967	SV Torrey Canyon	Hull breach, oil spills into the sea, ship bombed [47].
1978	MT Amoco Cadiz	Rupture of the hull plating, breakage of the hull, oil spills into the sea, destruction of the ship with deep-sea charges [48,49].
1979	Ixtoc I production platform	Oil spills into the sea, platform collapses [50].
1979	ST Atlantic Empress and ST Aegean Captain	Oil spills into the sea, death of 27 people, sinking of the *Atlantic Empress* [51].
1981	MV Tampomas II	Ship capsizes and sinks, 666 people die [52].
1986	MV Doña Paz and MT Vector	Sinking of both ships, death of about 4300 people [53].
1987	MF Herald of Free Enterprise	Ship capsizes, 193 people die [54,55].
1988	Piper Alpha production platform	Platform collapses, 167 people die [56].
1989	MT Exxon Valdez	Rupture of plating, oil spills into the sea [57,58].
1991	MV Salem Express	Shipwreck, deaths of around 470 people [59].
1993	MF Jan Hevelius	Ship capsizes and sinks, 55 people die [60].
1993	MF Neptune	Ship capsizes, death of about 1700 people [61].
1994	MF Estonia	Ship sinking, death of around 852 people [62].
1999	MV Erika	Hull breakage, ship sinks, leakage of hazardous substances into the sea [63,64].
2001	Petrobras 36 production platform	Sinking of a platform, death of 11 people, leakage of hazardous substances into the sea [65].
2002	MT Prestige	Hull breach, ship sinks, oil spills into the sea [66,67].
2002	MV Le Joola	Ship capsizes, deaths of about 1220 people [68].
2002	MV Tricolor and MV Kariba, MV Nikola, MV Vicky	Ship capsizes, loss of cargo, leakage of hazardous substances into the sea, sinking of the *Tricolor* [69–71].
2006	MV Al-Salam Boccaccio 98	Ship capsizes and sinks, 1161 people die [72,73].

Table 1. *Cont.*

Year	Unit Name	The Impact of the Disaster
2008	MV Princess of the Stars	Ship capsizes and sinks, death of about 814 people [74].
2010	Deepwater Horizon production platform	Platform capsizes and sinks, 11 people die, oil spills into the sea [75,76].
2011	MV Rena	Hull breakage, fuel leakage into the sea, loss of cargo [77,78].
2014	MF Sewol	Ship capsizes, 304 people die [79,80].
2019	MV Grande America	Ship capsizes and sinks, loss of cargo, fuel spills into the sea [81].

These are maritime disasters with severe consequences, which were selected on the basis of accepted criteria that capture the occurrence of several of the following consequences: loss of life by a large number of people, loss of cargo, fire and/or explosion, spill of hazardous substances and pollution of the environment, and sinking or major failure of a facility [31].

2.2. Method of Analysis

The detailed research method followed is illustrated in Figure 1 [20]. To map the stages of disaster development in the research, the authors chose the event network analysis presented by Håvold [38]. This method made it possible to divide each of the selected disasters into latent, initiating, escalating, critical, and energy release phases.

Moreover, the authors used FTA [82–84] to map the impact of the basic events on the occurrence of a given disaster phase. Although FTA is customarily used to analyse the structures of technical objects, the possibility of its application in process analysis was pointed out by Kuo and Zhu [85]. The authors of the aforementioned work cited examples of the use of metrics in, among other things, financial decision-making in management or risk analysis during the decision-making process.

Within the phases, the authors identified the basic events that made up the course of each phase. A basic event was defined as an event that was not subject to further decomposition during the conducted analysis, which described damage to system components, human (operator) errors, and impact on the environment [86].

Each phase mapped the state of the process during the course of the disaster. This is how the chronological cause-and-effect chain of the development of a given maritime disaster was constructed [32]. Building a causal chain first required establishing the chronology of events within the catastrophe, which was achieved by relying on the content contained in the post-accident commission report (if available), scientific articles and books, press releases, and marine unit databases. We referred to the National Transportation Safety Board, the Marine Accident Investigation Branch, the Danish Maritime Accident Investigation Board, Le Bureau d'enquêtes sur les événements de mer, the European Maritime Safety Agency, and Sea-web Ships by IHS Markit. For the planned analysis to be made possible at all, a unified (own) scheme of conduct for drawing up the description (decomposition) for all disasters was adopted.

The thesis was that, in the disaster population studied, there were dominant classes of basic events in each phase of the disaster process distinguished by the event network. To confirm the thesis, it was also necessary to determine the classes of events to which the basic events made up each phase of the disaster process, and to study the impact of each basic event on the occurrences of a particular disaster phase and a peak event [83]. An event class was the adopted systematic unit that included related types of basic events, distinguished on the basis of common characteristics.

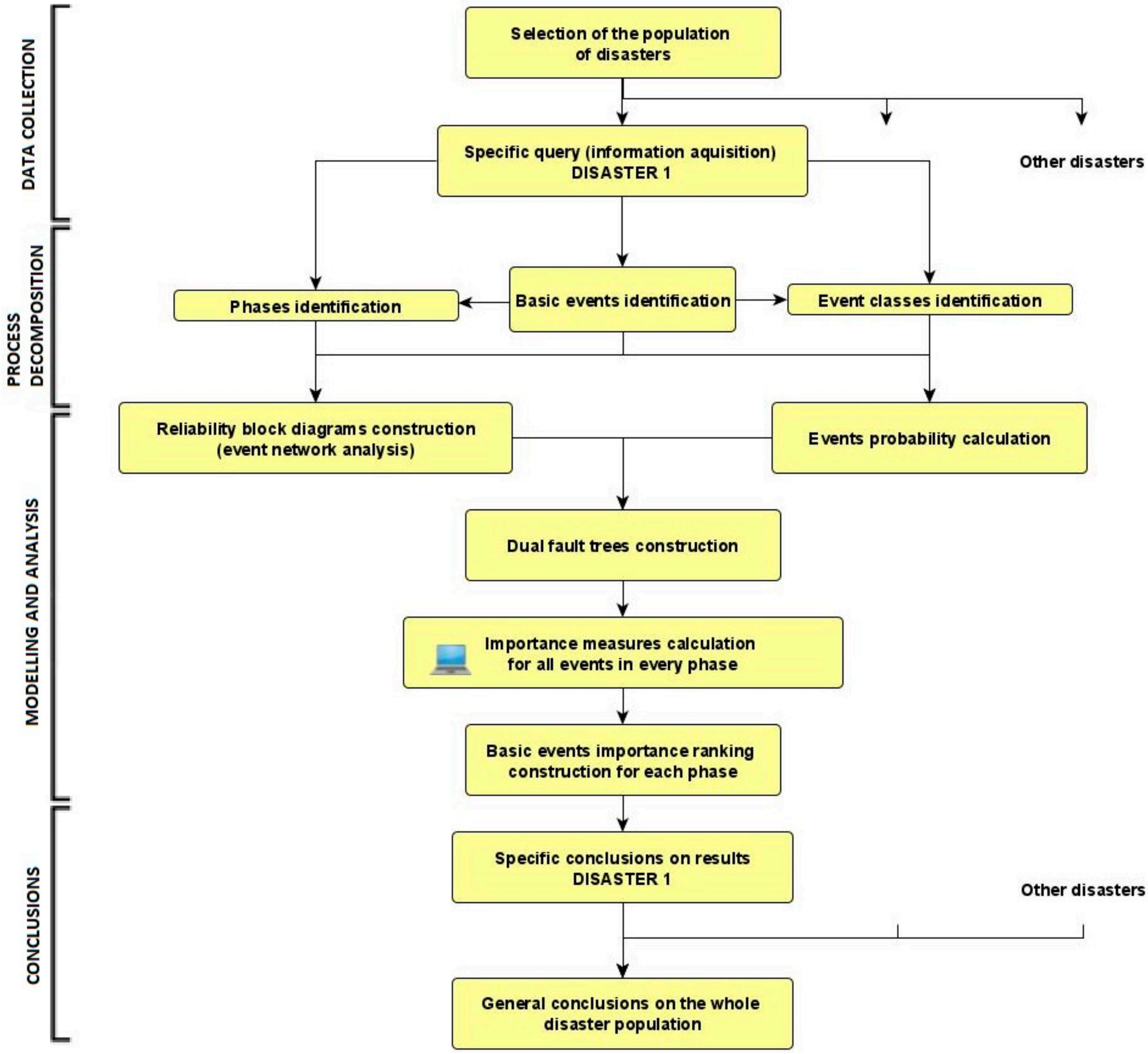

Figure 1. Flowchart depicting the research method.

2.3. Modelling and Analysis of the Course of Disasters

A total of 608 basic events were observed during the construction of cause-and-effect chains for the 30 maritime disasters studied. This allowed 44 classes of events to be identified and characterised, capturing human error, unfit equipment, and environmental impact. A detailed presentation of the adopted classes of events is presented in Table A1 in Appendix A. Classes of events were given terms (e.g., procedural error, pol. Błąd Proceduralny) and assigned two-letter abbreviations that were the first letters of the Latin alphabet (without Polish diacritics) of the main words pertaining to the class (e.g., BP). In cases where a particular combination of letters was already reserved for another class of events, or the class name was a single word, other letters were adopted to enable unambiguous labelling of the class (e.g., explosion—EX).

In parallel, each basic event in each phase of each disaster was assigned the class of event to which it belonged and its place in the causal chain according to the chronology of the disaster, so that (in the next step) it was possible to model the process structure of the course of each disaster.

The process of running 30 disasters was sequentially mapped using block diagrams, which were used to construct dual fault trees as auxiliary computational models. At the same time, to model the process of the course of a past disaster (repeat the process), it was necessary to apply to the model the the probabilities of basic events belonging to specific phases and create the process of the course of a given phase of a given disaster. It was assumed that the probability of a particular basic event should capture the fact that the event belonged to a particular phase of a given disaster and occurred in its process Pr(A), and that the event belonged to a particular class of XX events Pr(B). Thus, by analogy with the relationships presented, we have [83]:

$$\Pr(Z_i) = \Pr(A \ \wedge \ B) = \Pr(A) \cdot \Pr(B|A) = \Pr(B) \cdot \Pr(A|B) \tag{1}$$

Since the events A and B are independent, which means Pr(B | A) = Pr(B) and Pr(A | B) = Pr(A), then the probability of the basic event was:

$$\Pr(Z_i) = \Pr(A) \cdot \Pr(B) \tag{2}$$

The probability Pr(A) of a situation, such that a given event Z_i belongs to the j-th phase F_j, the m-th catastrophe K_m can be represented in formal form:

$$\Pr(A) = \Pr\left[(Z_i \in F_j) \wedge \left(F_j \subset K_m\right)\right] \tag{3}$$

To represent a situation that occurred in the past within the model, we assumed that a given basic event Z_i must occur in the modelled process if it occurred under real conditions in a disaster in the past that was a model of the given model. As a result, the modelled process followed the same pattern as the actual disaster that occurred in the past, that is:

$$\Pr(A) = \begin{cases} 1, \text{ when } Z_i \in F_j, \text{ where } F_j \subset K_m \\ 0, \text{ when } Z_i \notin F_j, \text{ where } F_j \subset K_m \end{cases} \tag{4}$$

Furthermore, the probability Pr(B) of the i-th event belonging to the XX class in a specific phase of a given disaster was equal to the quotient of the number of events belonging to the XX class in the F_j phase, which we denoted as n_{XXFj}, and the number of all the basic events belonging to the analysed F_j phase, which we signified as n_{Fj}, so that:

$$\Pr(B) = \Pr\left[(Z_i \in F_j) \wedge (Z_i \in XX) \wedge \left(F_j \subset K_m\right)\right] = \frac{m_{XXF_j}}{n_{F_j}} \tag{5}$$

However, the application of the above relationship for a large number of events resulted in a significantly complicated modelling process and vastly increased the risk of error at the modelling stage. We assumed (according to the statistical law of large numbers [87]) that, for a population of disasters striving to infinity and with the number of basic events striving to infinity, the proportion of basic events belonging to each class in each phase of each disaster approximated the proportion of events belonging to that class in the entire population of disasters. This was achieved by assimilating the individual basic events to each other, while not completing a detailed analysis at a lower level of decomposition (within an event class) and assessing the differences between events belonging to the same event class, that is:

$$\bigwedge_{\substack{n \to \infty \\ n_{F_j} \to \infty}} \frac{m_{XXF_j}}{n_{F_j}} \to \frac{m_{XX}}{n} \tag{6}$$

Thus, the probability Pr(B) of the i-th event belonging to class XX was equal to the quotient of the number of occurrences of the event belonging to class XX in the entire population under study relative to the total number of all observed events in the entire population of disasters, according to the formula [20]:

$$\Pr(B) = \Pr(Z_i \in XX) = \frac{m_{XX}}{n} \tag{7}$$

where m_{XX} represents the number of all events belonging to class XX in the entire population of disasters and n denotes the number of all events in the entire population of disasters. The above argument can be presented in a formalised form:

$$\bigwedge_{\substack{Z_i \in F_n \\ F_n \subset K_m}} \Pr(Z_i) = \Pr\left[(Z_i \in F_j) \wedge \left(F_j \subset K_m\right)\right] \cdot \Pr(Z_i \in XX) \tag{8}$$

Hence, the probability of the occurrence of the i-th basic event in the case in question (for the assumptions made) was equal to the probability of the basic event Z_i belonging to the specified class XX, and it was equal to:

$$\Pr(Z_i) = \frac{m_{XX}}{n} \tag{9}$$

A summary of each class, the number of basic events belonging to a given class of events, and the determined probability of occurrence of each basic event in the studied population of events are summarised in Table 2.

Table 2. Quantitative characteristics of the classes of events in the study population of disasters.

Event Class	Number of Occurrences of Basic Event in the Analysed Population	Probability of Basic Event
BE—Operational error	19	0.0313
BK—Structural error	13	0.0214
BN—Navigation error	15	0.0247
BP—Procedural error	42	0.0691
BW—Workmanship/production error	1	0.0016
CB—Man overboard	2	0.0033
CF—Negative physical factors	27	0.0444
CP—Psychological factor	22	0.0362
DS—Object drift	4	0.0066
EX—Explosion	12	0.0197
KD—Contact with the seabed	3	0.0049
KO—Collision/contact with another object	11	0.0181
NO—Unsuccessful repair/renovation	4	0.0066
NK—Ineffective modification of the structure	10	0.0164
NM—Excessive speed	6	0.0099
NN—Ineffective navigation manoeuvre	18	0.0296
NP—Unexpected navigational obstacle	5	0.0082
NR—Ineffective rescue/emergency procedure	47	0.0773
NU—Inefficient equipment	18	0.0296
NW—Inappropriate equipment	7	0.0115
OK—Weakening of the mechanical structure	7	0.0115
OP—Reduced psychomotor performance of the operator	7	0.0115
PJ—Object overloading with cargo/passengers	7	0.0115
PK—Hull breaking	5	0.0082
PL—Movement of cargo/passengers	5	0.0082
PO—Fire	22	0.0362
PS—Object heel	31	0.0510
RP—Rupture of/damage to hull plating	14	0.0230
UE—Damage to the on-board power plant	4	0.0066
UG—Damage to the main propulsion	5	0.0082
UL—People trapped below deck/inside the hull	3	0.0049
UM—Loss of manoeuvrability	4	0.0066
UP—Damage to auxiliary equipment	25	0.0411
US—Capsizing	11	0.0181
UZ—Loss of life	20	0.0329
WH—Extreme hydro-meteorological conditions	32	0.0526

Table 2. *Cont.*

Event Class	Number of Occurrences of Basic Event in the Analysed Population	Probability of Basic Event
WM—Material defect	2	0.0033
WN—Incomplete knowledge/no knowledge	9	0.0148
WS—Leakage of dangerous substances	16	0.0263
ZC—Change in stability characteristics	22	0.0362
ZP—Compartment flooding	29	0.0477
ZS—Object sinking	19	0.0313
ZT—Ship trim/change of trim	5	0.0082
ZZ—Ignoring the threat	16	0.0263
SUM:	608	1.0000

2.4. Determination of the Importance of Basic Events in the Phases of the Course of Disasters

The dual fault tree of each disaster, along with the calculated probabilities, made it possible to calculate measures for the importance of the basic events in all phases of all disasters using Sydvest Software's CARA FaultTree Application v. 4.1 Academic Edition. This software belongs to the RAMS (reliability, availability, maintainability, and safety) group of computer-aided reliability calculations [88,89]. Many alternatives are available, such as the advanced Reliasoft Synthesis BlockSim (HBM Prenscia, Tucson, AZ, USA), Reliability Workbench (Isograph Inc., Manchester, UK), and Windchill FTA (PTC Windchill Quality Solutions, Boston, MA, USA) packages.

The choice of software was dictated by the software being functionality appropriate for the stated purpose of the analysis, having a relatively simple user interface, and the availability of a free version for academic use. It is also not insignificant that the software is used in risk analyses of ships and oceanographic facility operations by one of the largest classification societies, DNV.

The use of several measures of importance was intended to best represent the ranking of events. Birnbaum's structural and reliability measure, the Vessley–Fussel measure, criticality measure, and improvement potential were calculated [85]. To test the thesis, it was assumed that a more optimal representation of the impact of basic events on the occurrence of each phase of the disaster would be given by indicators determined for individual phases, rather than for the entire tree. The application of the aforementioned importance measures to process the analysis may be questionable against the background of their widespread use in analysing the structures of facilities [90], for example, to increase reliability, readiness, and improve safety [20]. We needed to determine the importance of the events that made up the process (the course of the disaster) and extended the use of these measures. Table 3 summarises the interpretation of the measures that were adopted for the process, which is relevant when confronted with the classical approach to analysing the structure of the object.

Table 3. Adopted interpretation of importance measures for process analysis.

Measure of Importance	Interpretation of the Measure in Relation to Analysis of the Structure of the Object (System)	Interpretation of the Measure in Relation to Process Flow Analysis
I^B $I_i^B(t) = Pr_{ZS}[t \mid Pr_i(t) = 1] - Pr_{ZS}[t \mid Pr_i(t) = 0]$	Measure indicates the increase in reliability for which the component contributes most to the reliability of the system.	Measure indicates the escalation of the probability of occurrence that the basic event contributes most to the occurrence of a given disaster phase.

Table 3. *Cont.*

Measure of Importance	Interpretation of the Measure in Relation to Analysis of the Structure of the Object (System)	Interpretation of the Measure in Relation to Process Flow Analysis
I^{BS} $I_i^{Bs}(t) =$ $I_i^B[t \vert Pr_1(t) = Pr_2(t) = \ldots Pr_n(t) = 0.5]$	Interpretation analogous to I^B, except all components are assumed to have the same reliability of 0.5.	Interpretation analogous to I^B, except all basic events are assumed to occur with the same probability of 0.5.
I^P $I^{IP}(Z_i) = I^B(Z_i) \cdot Pr(Z_i)$	Interpretation analogous to I^B, except the reliability of the element is also taken into account.	Interpretation analogous to I^B, except the probability of a basic event is also taken into account.
$I^{V\text{-}F}$ $I_i^{VF}(t) \approx \frac{\sum_{j=1}^{m_i} \check{Pr}_j(t)}{Pr_{ZS}(t)}$	Measure indicates which element is most likely to contribute to system damage (the minimum cross-section containing the element).	Measure indicates which basic event with the highest probability contributes to the occurrence of a given phase of the disaster (the minimum path containing the basic event).
I^C $I_i^C(t) = \frac{I_i^B(t) \cdot Pr_i(t)}{Pr_{ZS}(t)}$	Measure indicates the probability that failure of a component results in system failure.	Measure indicates the probability that the occurrence of a given basic event results in the occurrence of a given disaster phase.

In the above method, rankings of the importance of the basic events in the five phases of the process of the course of each disaster were created. This made it possible to collate the most important classes of events in the five phases of the disaster process and to accept the thesis as true.

3. An Example Analysis of a Selected Disaster

An example decomposition, according to the approach described above, is shown in Table 4 for the 1994 MF Estonia disaster. All analysed disasters are presented in the dataset.

Table 4. Decomposition of the process of the course of a maritime disaster for the example of the MF Estonia ferry.

Phase	Description	Event Class	Denotation of Basic Event
Latent	The bow port gate has a design flaw (the design load on the bow port canopy and the assumed load distribution at the joints do not reflect the actual impact of sea waves).	BK	BK-1
Initiating	Canopy interlocks are not made as designed.	BW	BW-2
	On the day of the disaster, the wind was 18 m/s and the waves reached about 4 m high.	WH	WH-3
	Seawater pressure during the storm causes the deformation of the hinges and locks of the bow port canopy.	CF	CF-4
	The hinges and locking mechanism of the bow gate canopy are unable to hold the gate in the closed position.	NU	NU-5
	External forces are pushing on the canopy.	CF	CF-6
	The pressure of the canopy under the external forces causes the ramp to partially unseal, which relates to its design flaw.	UP	UP-7
	Water flows onto the car deck through the unsealed ramp.	ZP	ZP-8

Table 4. *Cont.*

Phase	Description	Event Class	Denotation of Basic Event
Escalating	Ship maintains full speed.	NP	NP-9
	Signalling indicators show the closed status for the bow port canopy and the ramp located on the bridge does not indicate unsealing.	NU	NU-10
	The canopy is not visible from the navigation bridge.	WN	WN-11
	The unsealed port is visible on the CCTV system monitors on the engine room's manoeuvring and control panel, but the engine room crew does not report the problem to the bridge.	BP	BP-12
	Under the water pressure, the gate breaks and falls into the sea.	UP	UP-13
	Water flows in through the ramp.	ZP	ZP-14
	Under the influence of an enormous amount of water, the car deck is flooded.	ZP	ZP-15
	The ship has a heel of about 15 degrees to starboard, which continues to increase.	PS	PS-16
	Watch officers reduce the ship's speed and make a turn to the port side.	NN	NN-17
	Officers instruct the mechanics to compensate for the heel by using the ballast system.	NR	NR-18
	Ballast system does not work due to air intake by the pumps.	NU	NU-19
	Watch officers close the watertight bulkheads.	NR	NR-20
Critical	The ship now has an approximate 30-degree heel to the starboard.	PS	PS-21
	Both main engines, one after the other, stop due to a drop in the lubricating oil pressure, which is associated with the excessive tilt.	UG	UG-22
	The crew on the bridge broadcasts an SOS signal and declares a lifeboat alert, but an organised rescue operation is not underway.	BP	BP-24
	In many cases, rescue equipment does not work.	UP	UP-25
	Ship's lifeboats cannot be lowered due to the heeling.	NR	NR-23
	Many passengers are trapped below deck.	UL	UL-26
	Ship drifts starboard toward incoming sea waves.	DS	DS-27
	Ship now has a heel of more than 40 degrees.	PS	PS-28
Energy release	The windows and doors of the stern superstructure on the starboard side are destroyed.	RP	RP-29
	Unsealed windows and doors cause the rooms to sink.	ZP	ZP-30
	Ship's power plant is flooded and stops operating.	EU	EU-31
	The ship's tilt continues to increase.	PS	PS-32
	Due to the heeling, the Estonia begins to sink (starting with the stern); within a few minutes, the ship has a heel of about 80 degrees, after which it sinks.	ZS	ZS-33
	852 people die.	UZ	UZ-34

Figure 2 shows an example of a flowchart that was created for the process of the MF Estonia disaster; Figure 3 shows an example of a dual fault tree for this disaster.

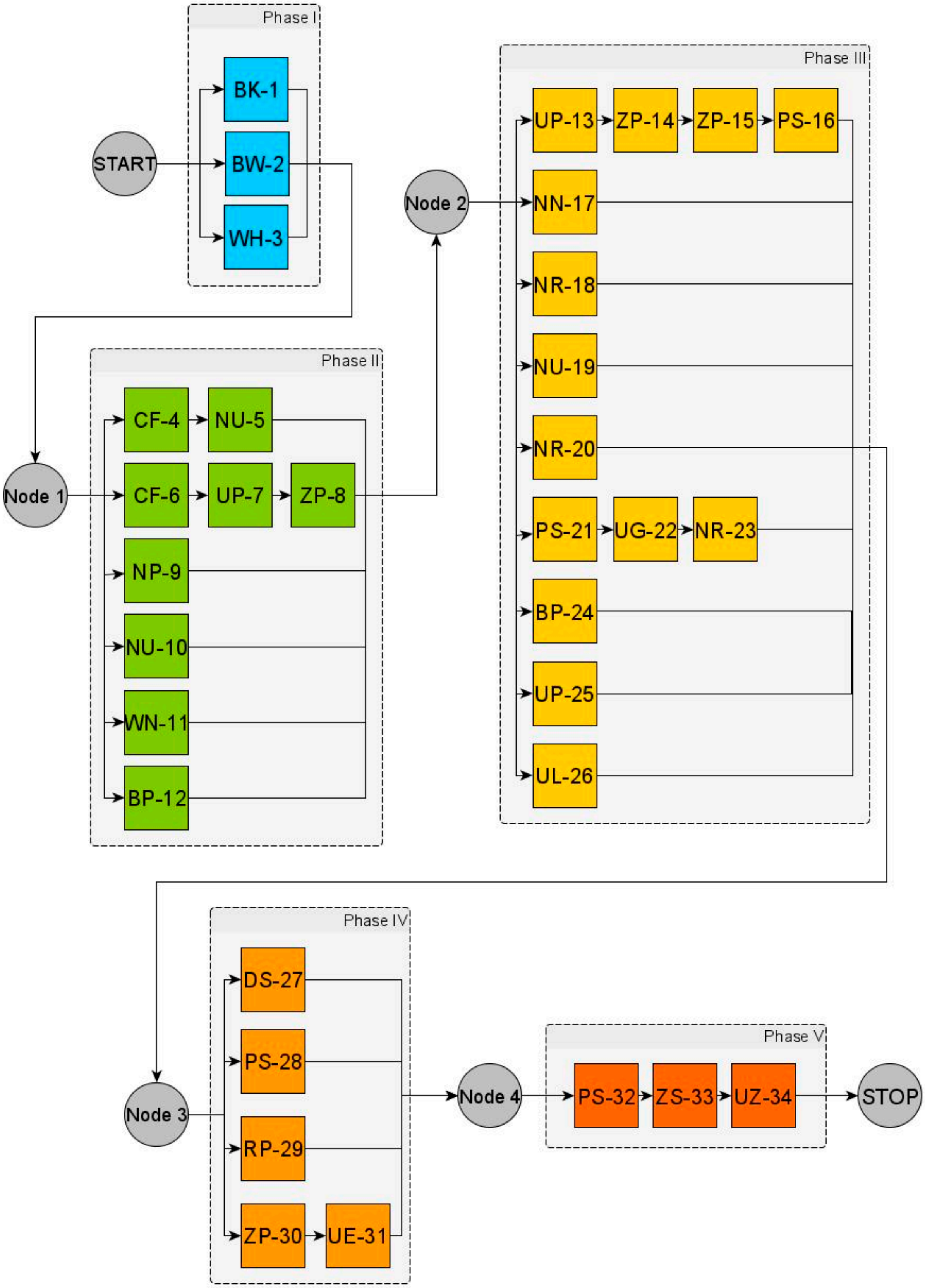

Figure 2. Block diagram for the process of the *MF Estonia* disaster.

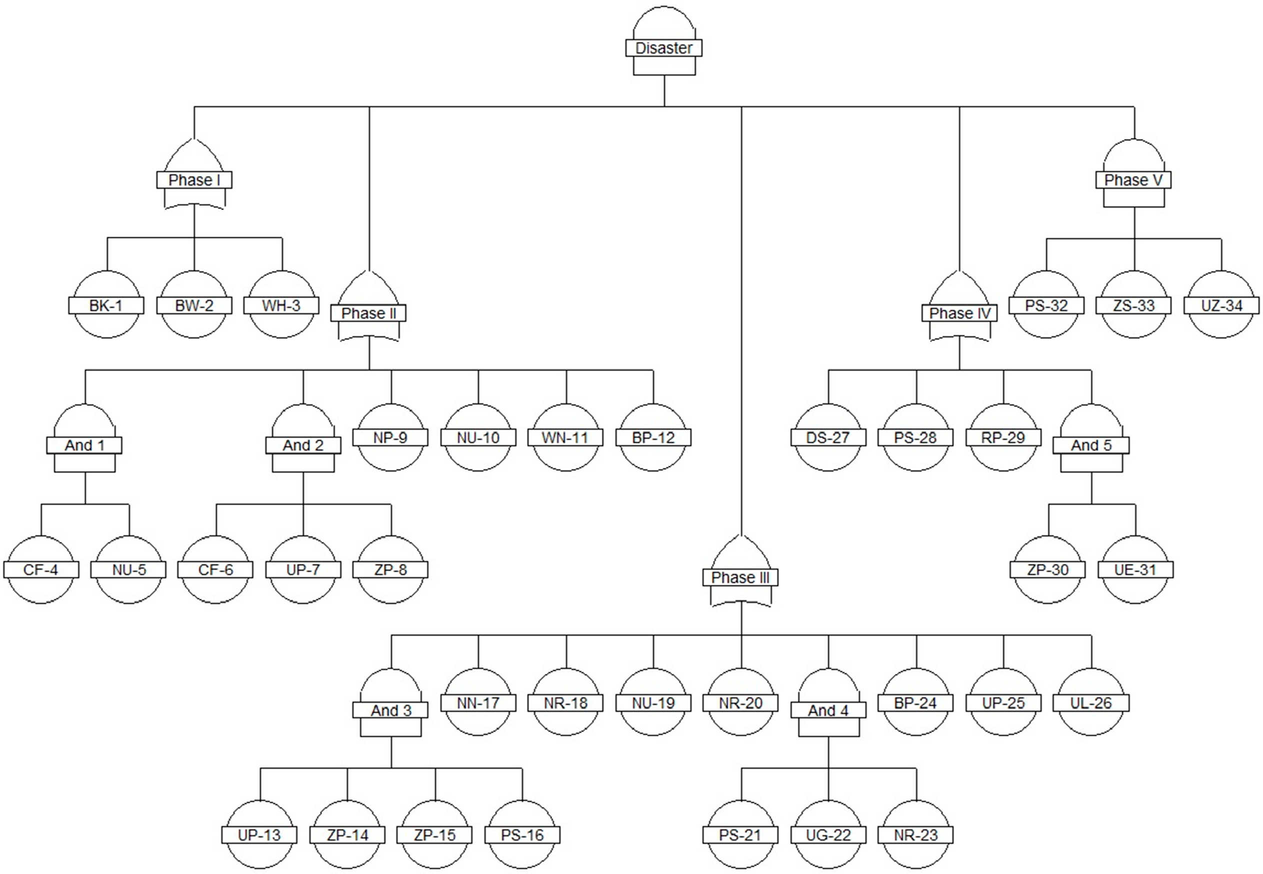

Figure 3. Dual fault tree for the process of the MF Estonia disaster.

The aforementioned calculated measures of importance enabled the ranking of the importance of basic events in each phase of each disaster. An example of the ranking for the Estonia ferry is shown in Table 5.

Table 5. Ranking of the importance of events in each phase of the MF Estonia disaster.

Phase	I^B	I^{Bs}	I^{VF}	I^{CR}	I^{IP}
Latent	WH-3; BK-1; BW-2	WH-3, BK-1, BW-2	WH-3; BK-1; BW-2	WH-3; BK-1; BW-2	WH-3; BK-1; BW-2
Initiating	BP-12; NU-10; NP-9; WN-11; NU-5; CF-4; UP-7; CF-6; ZP-8	BP-12, NU-10, NP-9, WN-11; NU-5, CF-4; UP-7, CF-6, ZP-8	BP-12; NU-10; NP-9; WN-11; NU-5, CF-4; UP-7, CF-6, ZP-8	BP-12; NU-10; NP-9; WN-11; NU-5, CF-4; UP-7, CF-6, ZP-8	BP-12; NU-10; NP-9; WN-11; NU-5, CF-4; UP-7, CF-6, ZP-8

Table 5. *Cont.*

Phase	I^B	I^{Bs}	I^{VF}	I^{CR}	I^{IP}
Escalating	NR-18, NR-20; BP-24; UP-25; NN-17; NU-19; UL-26; UG-22; PS-21; NR-23; UP-13, PS-16, ZP-14, ZP-15	NR-18, NR-20, BP-24, UP-25, NN-17, NU-19, UL-26; UG-22, PS-21, NR-23; UP-13, PS-16, ZP-14, ZP-15	NR-18, NR-20; BP-24; UP-25; NN-17; NU-19; UL-26; UG-22, PS-21, NR-23; UP-13, PS-16, ZP-14, ZP-15	NR-18, NR-20; BP-24; UP-25; NN-17; NU-19; UL-26; UG-22, PS-21, NR-23; UP-13, PS-16, ZP-14, ZP-15	NR-18, NR-20; BP-24; UP-25; NN-17; NU-19; UL-26; UG-22, PS-21, NR-23; UP-13, PS-16, ZP-14, ZP-15
Critical	PS-28; RP-29; DS-27; EU-31; ZP-30	PS-28, RP-29, DS-27; EU-31, ZP-30	PS-28; RP-29; DS-27; EU-31, ZP-30	PS-28; RP-29; DS-27; EU-31, ZP-30	PS-28; RP-29; DS-27; EU-31, ZP-30
Energy release	ZS-33; UZ-34; PS-32	ZS-33, UZ-34, PS-32	ZS-33, UZ-34, PS-32	ZS-33, UZ-34, PS-32	ZS-33, UZ-34, PS-32

Classes of events were ranked from most to least important (separated by semicolons). A comma separates measures of the same value.

4. Results and Discussion

The analysis of the developed models, as well as the event importance ranking developed for the different phases of each disaster, made it possible to list the most important classes of events, as shown in Figures 4–8. In the latent phase (Figure 4), the dominant class of basic events was the procedural error class, which accounted for 68% of the most important events in the studied disaster population.

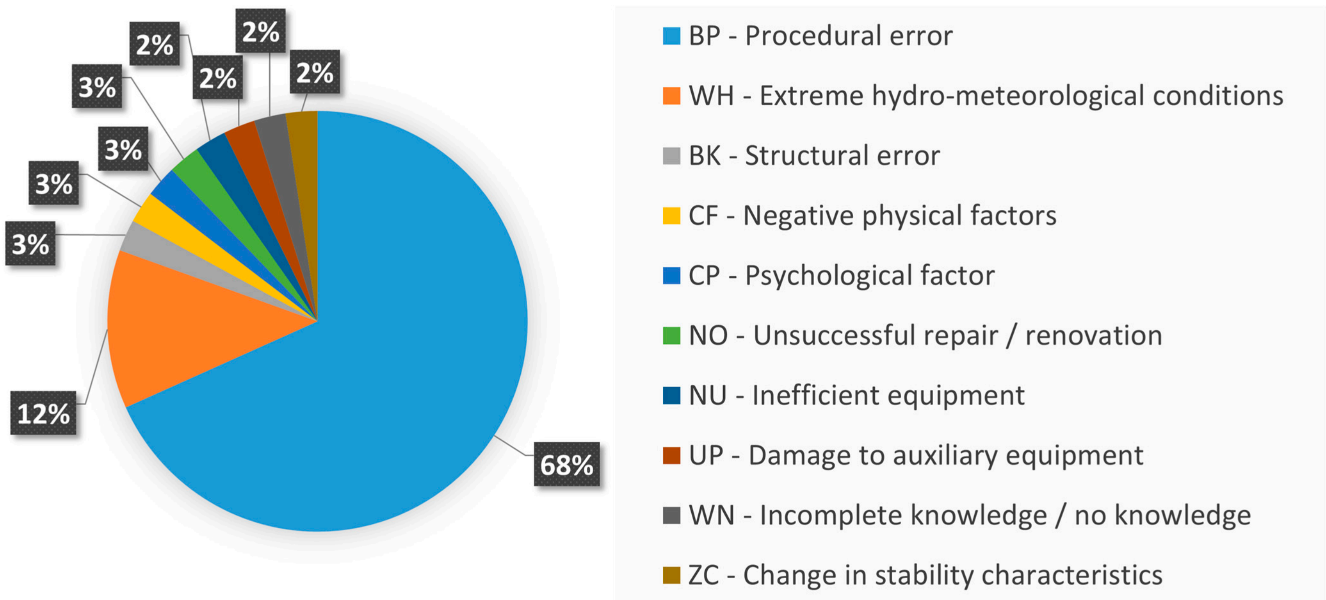

Figure 4. The most important events in the latent phase of the studied disaster population.

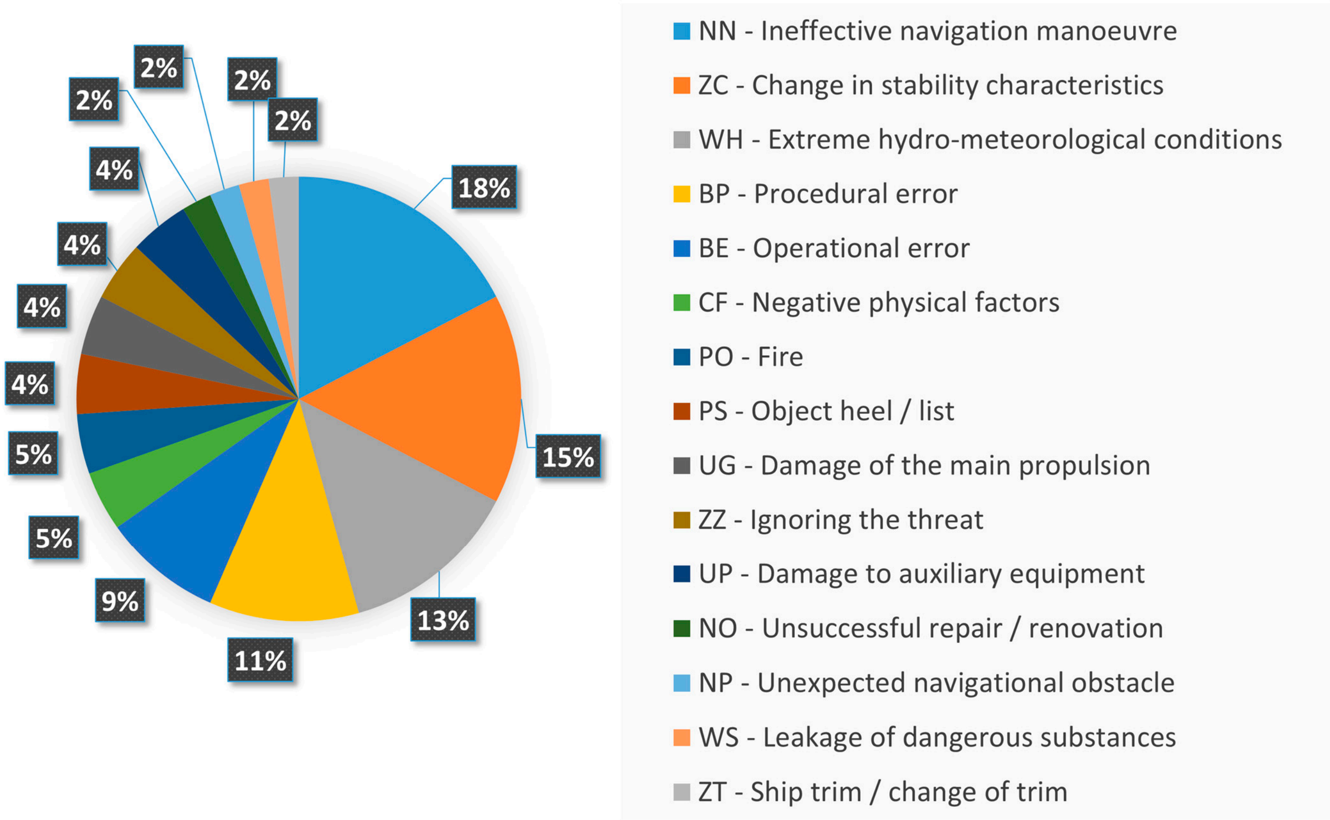

Figure 5. The most important events in the initial phase of the studied population of disasters.

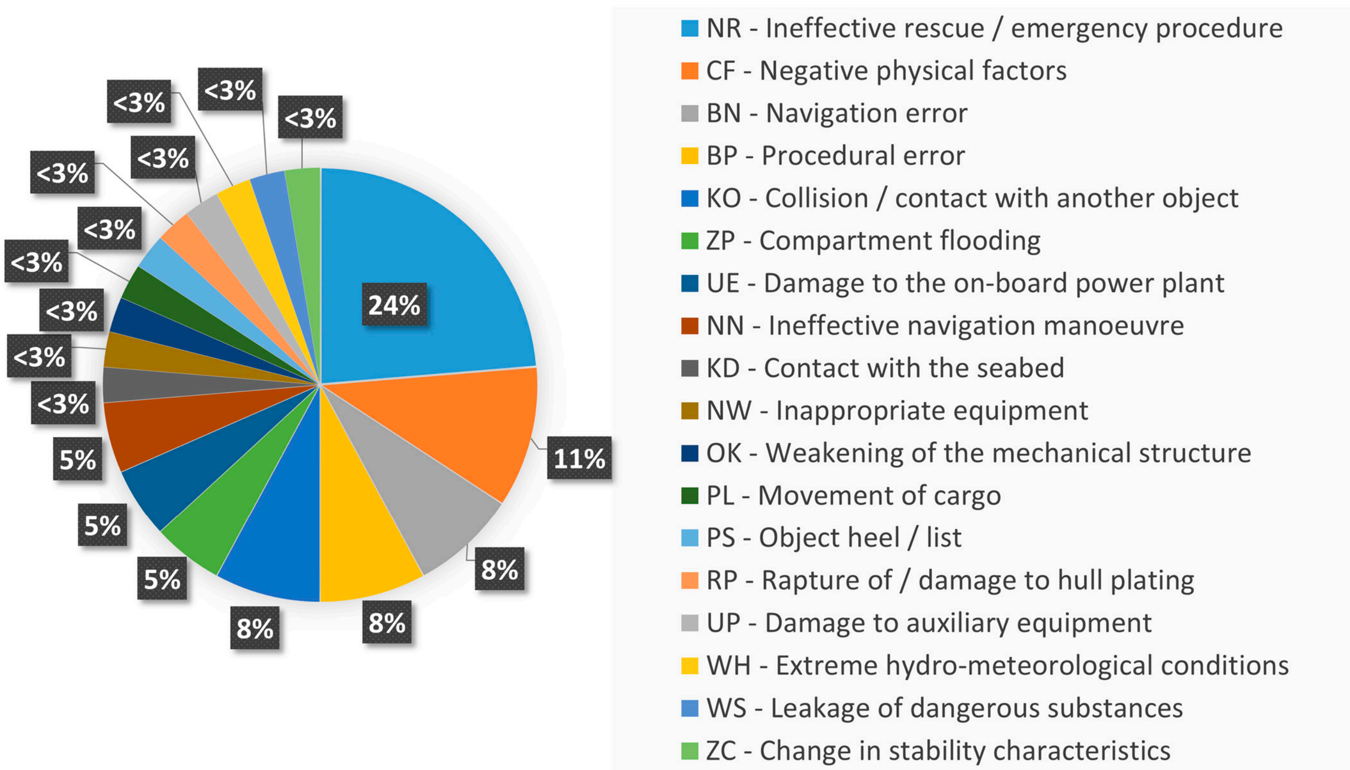

Figure 6. The most important events in the escalating phase of the studied population of disasters.

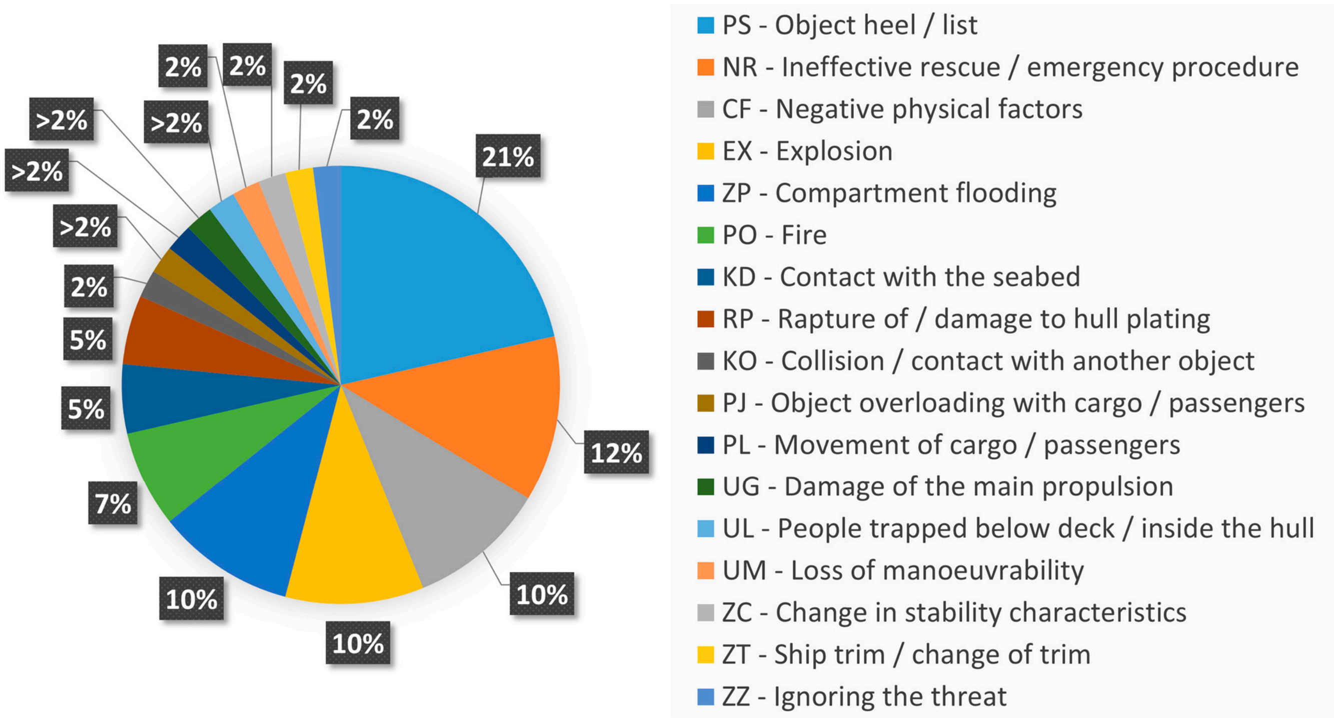

Figure 7. The most important events in the critical phase of the studied disaster population.

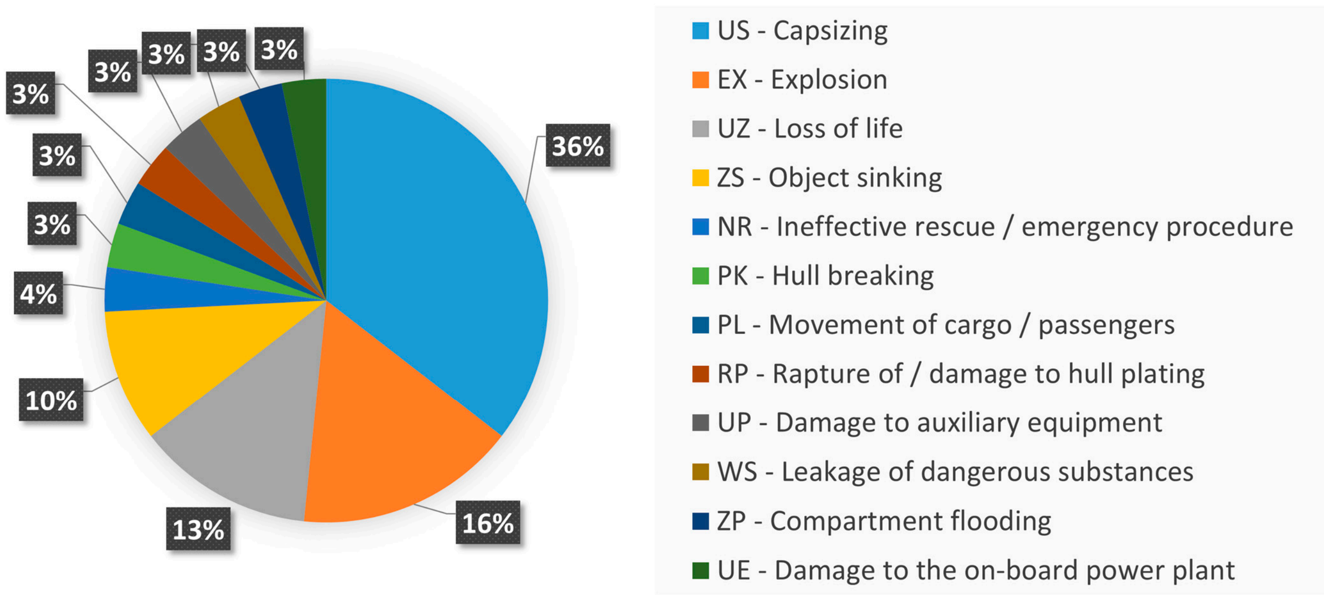

Figure 8. The most important events in the energy release phase of the studied population of disasters.

In the initial phase (Figure 5), there were several dominant classes of basic events in the studied population of disasters. More than 50% of all important classes belonged to four classes (Figure 5): "ineffective navigational manoeuvre" (18%), "change in stability characteristics" (15%), "extreme hydro-meteorological conditions" (13%), and "procedural error" (11%).

There were several dominant classes of basic events in the escalating phase (Figure 6) in the studied population of disasters. More than 50% of all important classes belonged to five classes, of which three classes had equal importance (Figure 6): "ineffective rescue/failure procedure" (24%), "negative physical factors" (11%), "navigational error" (8%), "procedural error" (8%), and "collision/contact with another object" (8%).

In the critical phase (Figure 7), there were several dominant classes of basic events in the studied disaster population. More than 50% of all important classes belonged to five classes, of which three were of equal importance (Figure 7): "object heel/list" (21%), "ineffective rescue/failure procedure" (12%), "negative physical factors" (10%), "explosion" (10%), and "compartment flooding" (10%).

In the energy release phase (Figure 8), there were two dominant classes of events in the studied disaster population, amounting to more than 50% of all important classes: "capsize" (36%) and "explosion" (16%). It is also noteworthy that among all the important classes of events, in addition to the two classes mentioned above, two more classes were important: "loss of life" (13%) and "object flooding" (10%). These four classes of events represented 75% of the important classes of events for the energy-release phase.

A detailed analysis of the disaster process conducted on a population of 30 selected maritime events, which occurred in the period 1912–2019, using event network analysis and FTA, revealed the existence of strong relationships between the phases of the disaster process. The study also showed correlations between the basic events in each of the five phases distinguished by the event network.

The added value of the proposed approach lies in the introduction of methods previously used in functional analysis for modelling the structures of systems into the analysis of process flows. Due to the habit of many researchers of applying only certain tools to describe processes or other scholars only describing the structure of the system, peculiar principles for the use of particular methods have emerged. It is thus relatively rare to observe new applications of so-called recognised methods that have strictly described applications. An example would be the proposed use of reliability block diagrams (RBD) to describe processes instead of their "standard" use in the description of structures.

5. Conclusions

An analysis of the importance of the basic events in each phase of the disasters showed that the most common basic events were not always the most important based on their contribution to the occurrence of each phase of the disaster. Indeed, an analysis of the studied population of disasters showed that among all the decomposed 608 basic events, the most common basic events belonged to classes such as ineffective rescue and/or emergency procedures, procedural errors, extreme hydro-meteorological conditions, and object heel/list (Tables 3 and 4).

In most cases, division of the process of the course of a disaster (into five phases (according to the assumptions of the event network analysis) was possible, which led to the conclusion that there was a connection between the occurrence of failures in the latent phase and the subsequent occurrence of a disaster (dormant factors weaken the safety of the system and, in combination with an active factor, lead to a disaster).

Accidents at sea were the result of the malfunctioning of the safety control system as a whole—they arose due to the occurrence of dysfunctional interactions between the elements of the system, which was proven by a detailed description and breakdown of the process of the course of each disaster in the studied population. A ranking of the importance of the basic events indicated the most important basic events in each phase of the process of the course of the disaster that led to the peak event. Analysing in detail the individual models of the disasters (studied structurally), it could be observed that they were complex, multi-element structures. The constructed models showed that the different phases of the disaster process proceeded in a serial, parallel, or mixed manner.

Through the application of importance measures, it was possible to identify the most important events in the process of the development of 30 maritime disasters, compared to its previous use in the analysis of technical objects. Disasters with the consequences mentioned in the introduction (loss of life of a considerable number of people, loss of cargo, fire and/or explosion, leakage of hazardous substances and environmental pollution, sinking or serious failure of the facility) occurred on certain types of offshore vessels, such as production platforms, passenger ships, tankers, and car carriers, which (based on the search conducted earlier) enabled us to conclude that these floating and ocean-going facilities have the highest operational risk.

The analysis also showed that human error is only a part of a larger model of the course of a disaster at sea—it also consists of the inadequacy of the system or its elements, the lack of capacity of the organisation (in the case studied—the shipowner) to correct errors (including those flowing from the course of previous disasters), and the prevailing work culture in the organisation.

The analysis presented in the article is an example of the application of the author's proposed method. While increasing the size of the analysed population in accordance with the law of large numbers, the results obtained provide an increasingly better reflection of the analysed problem.

Analysing the accident data in more detail for the assumed specific region and/or type of object and/or the observation period will, in turn, make it possible to obtain detailed information on subgroups specified within the study population that may be of interest to researchers.

By applying a systems approach to the problem, analogous analyses using the presented method can be carried out in relation to catastrophes and accidents of objects other than ships.

The direction of future research using the proposed approach is to analyse the importance of events within a specific disaster (as opposed to the phases of the disaster) and to examine disasters of ships of different types. For future purposes, the combination of event network analysis and FTA can be used to search for the most important events in disasters of industrial facilities and transportation modes other than maritime transport.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Summary of classes of events obtained from the surveyed population of maritime disasters.

Event Class	Class Characteristics	Abbreviation
Operational error	Inefficient or inappropriate use or preparation of equipment; inducing the effect of free liquid surfaces; improper decisions regarding the use of equipment; carelessness when using equipment; improper ballasting of the unit.	BE
Structural error	Watertight bulkheads too low; multifunctional piping; leaky deck design; location of equipment out of sight of the operator; dependence of facility power supply on extracted or transported product; inadequate bow gate design for loading process; bow gate design not designed for wave action; poorly located vent line; lack of shut-off valves on vent lines; placement of portholes low above the waterline; too few ballast tanks; improper location of ballast tanks; the adverse impact of poorly located equipment on adjacent spaces.	BK
Navigation error	Too late or improper navigational manoeuvres; arbitrarily changing course contrary to accepted rules of navigation; entering shallow or shoal waters; misjudging the distance from an obstacle; erroneous course correction.	BN
Procedural error	Failure to apply or violation of procedures; procedures that do not meet quality standards; inadequate fire protection of equipment; inadequate training of crews; poor signage; poor location or poor quality of life-saving equipment; contractual disputes; lack of survey certificates/safety certificates or forged certificates; lack of licences; lack of qualified crews on board; inadequate crew size; lack of inspection activities or supervision; dangerous work being performed by adjacent facilities; lack of (consistency of) documents; lack of proper communication between crew/employees; improper lashing of cargo or failure to lash cargo at all; carelessness in ship management; the refusal of shelter or assistance by the port; illegal transport of passengers or unauthorised cargo.	BP
Workmanship/production error	Failure to follow or ignore design guidelines.	BW
Man overboard	Passengers and crew fall into the water; passengers are forced to jump into the water due to the situation.	CB
Negative physical factors	Excessive rise in the level of liquid, pressure or gas; lack of counter-pressure at the desired time; strong impact caused by wind or force of the water; intense rocking of the ship due to water movement and wind force; water pressure; dead wave action; (transmitted) vibration; sudden deterioration of the weather; evaporation of liquid; smoke; fumes of flammable gas; sudden rise in temperature; melting of equipment due to high temperature; escape of gas; gas intrusion.	CF

Table A1. *Cont.*

Event Class	Class Characteristics	Abbreviation
Psychological factor	Exerting pressures of various types (psychological, time, financial, etc.); risk homeostasis; panic; avoidance of confronting facts; delay relative to the accepted schedule; psychological inertia; failure of the lower-level crew to question erroneous decisions made by the higher-level crew; prevailing organisational chaos.	CP
Object drift	Pushing of the ship by strong winds against the manoeuvres undertaken.	DS
Explosion	Physicochemical agent; flammable charge; secondary explosions; explosion caused by misoperation of equipment; explosion caused by (released) gas.	EX
Contact with the seabed	Sailing into the reef.	KD
Collision/contact with another object	Brushing against another object; hitting the side of another object; hitting a rock; impact with an underwater navigation obstacle.	KO
Unsuccessful repair/renovation	Failure to repair hydraulic system; failure to repair scrubber; inadequate or incorrect repair of equipment.	NO
Ineffective modification of the structure	Modification of the ballast system; relocation of equipment to another location; increase in the weight of the vessel; secondary increase in the vessel's cargo capacity; secondary adaptation of the facility to perform functions other than those originally designed; improper or adverse relocation of equipment or compartments; replacement of portions of the hull; adverse effects of modifications to escape routes.	NK
Excessive speed	Maintaining or developing a speed unsuitable for the prevailing conditions.	NM
Ineffective navigation manoeuvre	Properly undertaken manoeuvre that does not produce results.	NN
Unexpected navigational obstacle	Another vessel or object in the way of a manoeuvre or course; unexpected heavy ship traffic; crowding in the port channel.	NP
Ineffective rescue/emergency procedure	Evacuation alarm activated too late; rescue action or emergency procedure taken too late, not taken at all, or performed incompetently; improper use of preventive measures or use of improper measures; firefighting action is unsuccessful; continuing rescue action despite its unreasonableness; inability to carry out rescue action or apply rescue measures; ineffective transfer of liquid cargo; lack of human influence on automatic emergency procedure.	NR
Inefficient equipment	The parameters of either the device or the entire facility are unsuitable for (current) needs; the device does not work, malfunctions, or performs multiple functions and is damaged.	NU
Inappropriate equipment	Lack of sufficient number of lifeboats, rafts, or life-saving equipment; inadequate or insufficient life-saving equipment; lack of an alarm system; lack of radio communication and locating equipment; hull design unsuitable for the cargo carried.	NW

Table A1. *Cont.*

Event Class	Class Characteristics	Abbreviation
Weakening of the mechanical structure	Damage to watertight bulkheads, weakening of the structure due to fire, explosion, or corrosion; lack of fire resistance due to modification; deformation or rupture of bulkheads due to (increasing) pressure	OK
Reduced psychomotor efficiency of the operator	Effects of alcohol or psychoactive substances; fatigue; illness; falling asleep due to fatigue.	OP
Object overloading with cargo/passengers	The number of passengers or the quantity/volume/weight of cargo exceeds the permissible limit.	PJ
Hull breaking	Breaking across or along the ship.	PK
Movement of cargo	Loosening of cargo fastenings and movement/spillage of cargo; cargo falling overboard; movement of cargo due to external forces; shifting and tipping of cargo due to impact of the unit with another object.	PL
Fire	Friction causing sparks; sparks from the air-conditioning unit operating continuously at full capacity; ignition of compartment or deck due to physical and chemical agents; spontaneous combustion; spread of fire (to compartments or entire unit); oil fire (on water); ignition due to contact with hot engine room components; ignition caused by an explosion; ignition of gas.	PO
Object heel/list	Overturning caused by improper mustering of passengers; continuation of mustering during the effects of swirling liquid surfaces; flooding of the craft with water, the pressure of waves or gas on the craft; displacement of cargo; change of stability characteristics; sudden change of course; contact with another object.	PS
Rupture of/damage to hull plating	Destruction of the forepeak; ripping of the ship's hull plating; cutting or puncturing of the tank; cutting or tearing of the hull; destruction of fire bulkheads; destruction of windows or doors; unsealing of windows and doors; cracking of the deck or the hull.	RP
Damage to the on-board power plant	Loss of power supply due to flooding or fire in the generator room.	UE
Damage to the main propulsion	Inadequacy caused by damage, poor operation, material errors, fatigue wear, or as a result of being hit by another object; shutdown of the engine by the security system.	UG
People trapped below deck/inside the hull	Trapping of passengers or crew on the lower decks of a ship, below deck, or in a fireproof platform module.	UL
Loss of manoeuvrability	Ship is not responsible for its movements; ship is difficult to steer as a result of previous events of various types.	UM

Table A1. *Cont.*

Event Class	Class Characteristics	Abbreviation
Damage to auxiliary equipment	Loss of anchor; damage to (hydraulic system of) steering gear; rope breakage; mooring winch breakage; cable, pipeline breakage; damaged explosion-proof head; damage to firefighting equipment; non-functioning of radio equipment due to lack of power; compressor interruption due to prior errors of operators of other equipment; damaged or broken gate; unsealed ramp; non-functioning life-saving equipment; corroded ballast tanks; bulkhead damage; damage to (pipe, drainage) mains; tank deformation; door damage (seal, closure device); damage to hydrostatic lifeboat release system; unfit drainage pumps; unobstructed discharge scuppers.	UP
Loss of life	Death of passengers and/or crew; injuries.	UZ
Extreme hydro-meteorological conditions	Low water/surface temperature; track icing; fog; poor visibility; darkness; storm; high waves; strong wind; heavy rain; typhoon, eye of typhoon; sudden collapse of the weather.	WH
Material defect	Brittle rivets, mixing cement with gaseous nitrogen to accelerate cement setting.	WM
Incomplete knowledge/no knowledge	Lack of or incomplete knowledge of the crew about the modification made to the vessel or equipment; lack of or incomplete knowledge of the captain about the location of passengers, the condition of the equipment, or the failure of the crew to perform their duties; lack of or incomplete knowledge of the hydro-meteorological forecasts for the route taken; lack of knowledge of the crew about being on a collision course; lack of or incomplete knowledge of the crew about the operation of the equipment.	WN
Leakage of dangerous substances	Overturning of containers (containers and drums); release of substances due to an explosion or hull breakage/splitting of the hull by another object; leakage through piping systems; leakage from an unfit engine; leakage due to inadequate preventive measures; leakage from the wreckage.	WS
Capsizing	Ship/platform turns upside down.	US
Change in stability characteristics	Increased or insufficient draft limit of the vessel; change in metacentric height of the vessel; influence on stability characteristics through the movement of the crew, passengers, cargo, structural modification or hydro-meteorological conditions; overballasting or improper ballasting of the object.	ZC
Compartment flooding	Compartment flooding (engine room, propeller room and generator room); ship/platform/platform column flooding; deck flooding (passenger, car, and rail); hull flooding.	ZP
Object sinking	Ship or part of it (bow or stern) sinks; production platform collapses.	ZS

Table A1. *Cont.*

Event Class	Class Characteristics	Abbreviation
Ship trim/change in trim	Increase in draft at the bow due to flooding of the object with water; increase in trim (for cargo purposes, as a result of overballasting); trim of the ship due to inoperability of the ballast system.	ZT
Ignoring the threat	Ignoring of warning messages by the crew; carelessness of the crew; willful disobedience of instructions from the supervisor's or shipowner's procedures (ISM); ignoring defects in the vessel or equipment by its controllers, manager, shipowner, destination port administration, refuge or crew; concealing the poor condition of equipment or failure to control the vessel.	ZZ

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