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Fault-tree Models of Accident Scenarios of RoPax Vessels

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Abstract: Ro-Ro vessels for cargo and passengers (RoPax) are a relatively new concept that has proven to be popular in the Mediterranean region and is becoming more widespread in Northern Europe. Due to its design characteristics and amount of passengers, although less than a regular passenger liner, accidents with RoPax vessels have far reaching consequences both for economical and for human life. The objective of this paper is to identify hazards related to casualties of RoPax vessels. The terminal casualty events chosen are related to accident and incident statistics for this type of vessel. This paper focuses on the identification of the basic events that can lead to an accident and the performance requirements. The hazard identification is carried out as the first step of a Formal Safety Assessment (FSA) and the modelling of the relation between the relevant events is made using Fault Tree Analysis (FTA). The conclusions of this study are recommendations to the later steps of FSA rather than for decision making (Step 5 of FSA). These recommendations will be focused on the possible design shortcomings identified during the analysis by fault trees throughout cut sets. Also the role that human factors have is analysed through a sensitivity analysis where it is shown that their influence is higher for groundings and collisions where an increase of the initial probability leads to the change of almost 90% of the accident occurrence.

Keywords: Ship accidents, fault trees, human factors.

1 Introduction

The constant and persistent growth of competitiveness in the transport market reflects continued efforts to increase productivity and reduce cost levels. The European Union policy promoting short sea shipping in order to reduce road congestion and minimize environmental impact has led to the development of new concepts for ships. These governmental efforts for the development and promotion of short sea shipping are an attractive option towards this objective by replacing conventional low speed crafts.

In order to achieve this increasing need, the capacity and sailing speed of new Ro-Ro ships and sailing schedules were adapted to permit an optimization both to ports interfaces and ships themselves. Therefore, frequent adjustments on sailing schedules allowing more frequent sailings by optimizing departure and arrival times allow a qualitative increase on the capacity of response of these ships to the increasing demand. The development reduces transit times due to high speeds and installed power of these units, allowing delivery times to fit the customer's production schedule. Moreover, transport equipment is upgraded for freight handling in order to increase loading capability and to enable larger volumes to be transported with less space on board. These initiatives also help to reduce the number of lay-days in port and stevedoring costs per transported unit. In cooperation with the customers ways of minimizing the number of handling, operations and freight damage are sought.

However, many of these concepts are associated with the increased operational speed of ships. As speed at sea increases, risks of ship operation are also increased and safety is consequently challenged. According to Levander[1] the term 'RoPax' can be seen as a combination of the acronym 'ro-ro' (roll-on, roll-off), used for a freight ship where freight is driven on and off, and 'pax', a term for passenger. The passenger capacity of a RoPax ship is rather smaller, usually 200-800 passengers. A passenger liner with overnight cabins operating liner shipping routes in Northern Europe typically accommodates between 1,000 and 2,000 passengers. A RoPax ship therefore transports fewer passengers than a regular passenger liner, but can handle a freight volume, including space for transporting passengers' cars on a separate deck, comparable to that transported by a medium-sized freight ship with a freight capacity of about 2,000-2,500 lane-metres.

Although relatively new, the RoPax concept has proved popular in the Mediterranean region and, since the discontinuation of tax-free sales on board has increased interest in combining passenger and freight transport, the concept is becoming more widespread in Northern Europe. In terms of hull form and propulsion for fast RoPax ferries operating at up to 30-knot speed,

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*Corresponding author. *E-mail address*: guedess@mar.ist.utl.pt the displacement type hull form has proven the best choice. The displacement type hull forms are used for speeds corresponding to Froude numbers below 0,35[2].

New ship owners can maintain and even increase safety by placing higher demands on the operators (the crew) and the organisation. Ship operation places, then, new and higher demands on safety and prevention of accidents. The objective of this study was to identify hazards and the relationship between events that can lead to vessel casualties for RoPax vessels. The hazard identification is carried out as the first step of a Formal Safety Assessment (FSA). The conclusions in this study are meant as recommendations to the later steps of FSA rather than for decision making (Step 5 of FSA). These recommendations will focus on the possible design shortcomings identified during the analysis by fault trees throughout cut sets.

2 Fault tree analysis (FTA)

FSA is a powerful tool in helping to demonstrate that risks are tolerable and As Low As Reasonably Practicable (ALARP). An FSA analysis provides estimates of frequencies of hazardous events and provides insights into the most likely causes of such events, thus identifying any weaknesses in the protection provided. Models developed to perform an FSA can be used to support safety cases and to allow risk-informed decision making, such as modelling the timing and acceptability of equipment outages and prioritization of enhancement work. The risk analysis comprises two main activities: 1) probability modelling and 2) consequence modelling. Probability modelling uses standard techniques such as FTA and reliability block diagrams. Apart from establishing probabilities for a top level event, fault trees identify initiating events and how these combine to contribute to the top event. Consequence analysis is concerned with a detailed analysis of the possible developments resulting from a failure or from an accident. The FTA can be seen as a logical and graphical method highly used to evaluate the probability of one undesirable event or accident occurring as a result of failures of the different components of the system under analysis. It can be seen as a deductive approach, which starts from an effect and aims at identifying its causes. It starts with the event of interest, the top event, such as a hazardous event or equipment failure, and is developed from the top down.

The Fault Tree is a technique that can be used both for a qualitative and a quantitative analysis. Qualitatively it is used to identify the individual scenarios (so called paths or cut sets) that lead to the top (fault) event, while quantitatively it is used to estimate the probability (frequency) of that event. A component of a Fault Tree has one of two binary states, either in the correct state or in a fault state. A Fault Tree is basically the graphical representation of the Boolean (logical) equation which links the individual component states to the whole system state. The basic elements of a Fault Tree may be classed as (i) the top event, (ii) primary events, (iii) intermediate events and (iv) logic gates. By using the property of the Boolean algebra it is possible to establish the combinations of basic (components) failures which can lead to the top (undesirable) event when occurring simultaneously. These combinations are so called "minimal cut sets" and can be derived from the logical equation represented by the Fault Tree[3].

As a Fault Tree represents a logical formula it is possible to calculate the probability of the top event by ascribing probabilities to each basic event and by applying the probability calculation rules and the Boolean algebra properties[4]. When the events are independent and the probabilities are low, it is possible to roughly estimate the probability of the output event if an OR gate is the sum of the probabilities of the events of the input. On the same condition, the probability of the output event of a gate can be calculated as the product of the probabilities of the events of the input. On the other hand, the estimation of the top event probability is less accurate, more and more conservative, when the probabilities increase, even if the events are independent.

This kind of qualitative analysis is very powerful and interesting, but, unfortunately, for large and/or complex Fault Trees, it is rather difficult to extract these minimal cut sets. However, a large number of existing computer programs have been developed for finding the minimal cut sets in a more or less efficient way, resulting in exact results being able to handle very large Fault Trees and find minimal cut sets or prime implicants.

3 RoPax risk analysis

In this study, the first steps of the FSA methodology were applied for the several casualty events of RoPax/Ro-Ro ships. The hazard identification was then assessed through the application of fault trees, which allowed the identification of the basic events associated with each of the vessel related casualty. One has to bear in mind that hazards only become a problem when they develop into an accident and in general, this is only possible when a sequence of events occur.

As hazard identification is an essential part of the risk assessment process, a list of relevant hazards was identified. For the RoPax/Ro-Ro case, the following set of vessel related casualties were considered:

- Collision
- Grounding
- Fire explosion
- Capsize

The choices of these casualty events were derived from statistical data from accidents involving passenger ships (collisions and groundings) as statistics from RoPax vessels were not available. Also, analysis involving events that could result in high human casualty or structural damage will be analysed.

The collision events are among the most common ship accidents and continuous efforts have been made to prevent this event or mitigate the associated consequences. However, collisions are likely to happen in the future and therefore, tools for the analysis are continuously being developed and/or refined.

In recent years, there has been a rapid development of new navigational systems. A growing number of VTS systems are established around the world. Extensive trials have been carried out with a sole lookout during the night on ship bridges. The IMO has introduced requirements for new ships to fulfil particular manoeuvrability criteria whilst a new generation of large fast ferries has emerged. It is generally agreed that all these activities have considerable influence on the probability of ship accidents in the form of collisions[5].

Collision can be defined as a ship striking or being struck by any self propelled ship whilst at sea whether the ship is in transit or anchored and excludes collisions with any underwater vessel/wreck and self propelled oil installations. Possible relationships for the collision variables expressed in the analysis are illustrated in Table 1.

Table 1 Accidental events/loads

Cause contributors	Consequence contributors
Poor visibility	Flooding
Rough weather	Heeling
Navigational confusion	List
Navigational error	Grounding
Unauthorized route	Cargo shift
Failure to use radar	Flammable cargo
Radar failure	Fire
Excessive speed	Engine failure
Steering failure	Power failure
Engine failure	Low stability
Power failure	Open watertight doors
Poor bridge layout	Lifeboat failure
Inexistence of redundant systems	Inaccurate mayday
	Delayed mayday
Low manning levels	Rough weather
Poor crew training	Poor visibility
Poor level of maintenance	Low temperature
Inexistence of vessel traffic systems	Stabilising tank control failure
Traffic densities	Inadequate structural design
Poor bridge layout	Emergency drainage failure
	Capsize
	Inadequate structural arrangement

From Table 1, one may see that the most influential effects on collisions are human factors, navigation aids, manoeuvrability, and system failures, although there are other events or loads that can influence the outcome of a collision. For instance, the ship's ability to stay afloat after damage is the most important safety related aspect along with the location of bulkheads as it is one of the most important design parameters. Therefore, a very strong link exists from collision to damage survivability. Obviously, these factors are dependent upon the geographical position or type of vessel, but they still represent a reference for the identification of causes associated with a collision event. One may see that most of the causes identified were related to human factor issues like improper lookout, non-compliance with marine traffic rules, or failure to sound signals.

The next stage of this work is to define a list of prioritised hazards for the RoPax vessels from which we will create a scenario, thus illustrating a way to dispose of a hazard and exhibit the consequences of this hazard including human factors. This was completed by using an FTA method. The software used[6] is a complete tool for performing a wide range of operating dependability studies from probabilistic studies or incident studies (handling higher probabilities, close to 1). It also allows one to define a specific probability parameter (distribution) for each of the basic events involved in the FTA (see Fig. 1 to Fig. 5).

In this analysis, two sets of probability parameters were used, namely: exponential distribution used for mechanical, equipment, and design failures, and a constant probability for human or management failures and errors. The exponential distribution was used for mechanical failure due to the fact that it describes a constant failure rate. This property means that the probability that a specific device will fail during a future period in time is independent of its age. Since the probability of failure in a specific time interval is independent of the age, failures occur by external shocks to the device, as such they are random failures.

Due to the unavailability of reliable data of failure rates for each of the basic events, a constant failure equal to 0.0004 for human and 0.0001 for mechanical elements was assumed. For the human basic events, this value corresponds approximately to the nominal human unreliability proposed by the Human Error Assessment and Reduction Technique[7] for completely familiar routine tasks. For equipment and machinery components, the failure rate corresponds to a Mean Time to Failure of 10000 hours, assuming an exponential distribution. However, it should be clear that the main objective of this study is not the determination of the probabilities for each of the casualty events analysed but the ident-

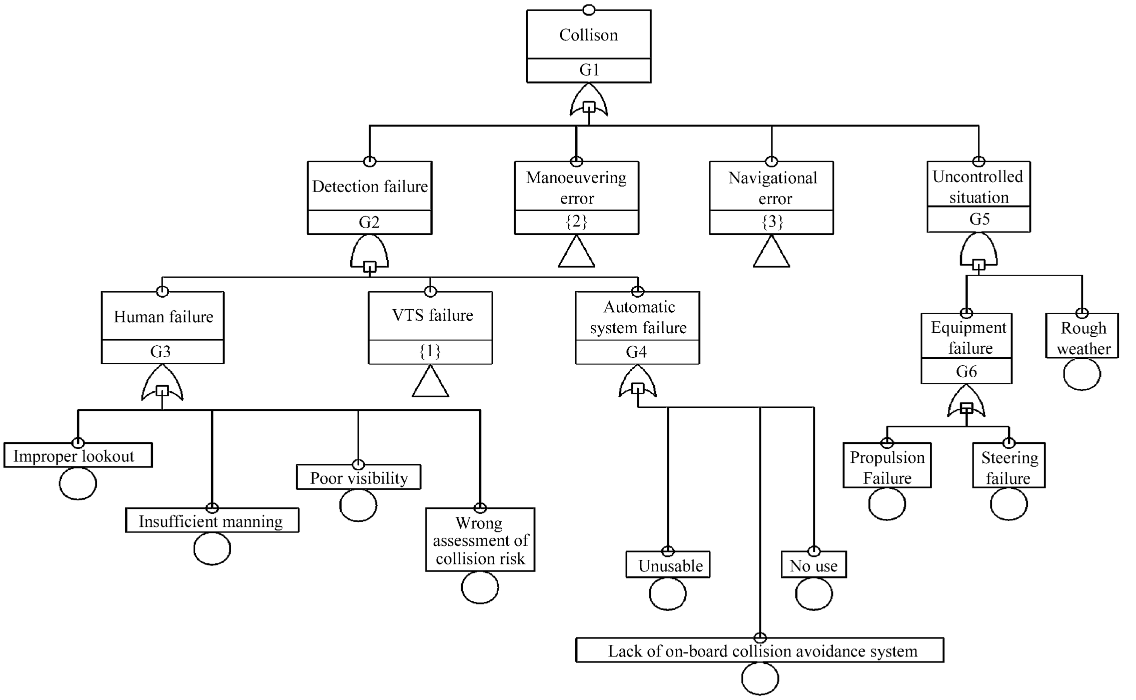

Fig. 1 Developed fault tree – collision terminal event

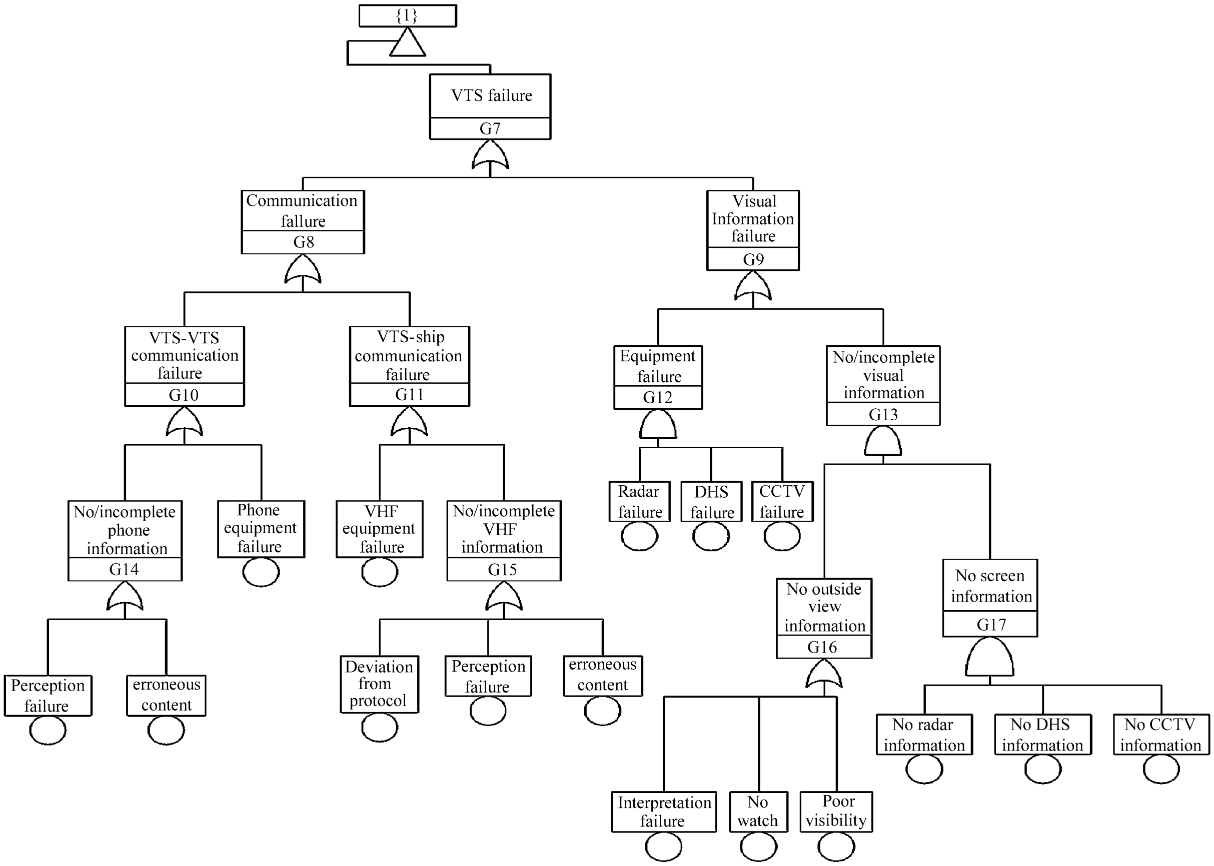

Fig. 2 Developed fault tree (continued)

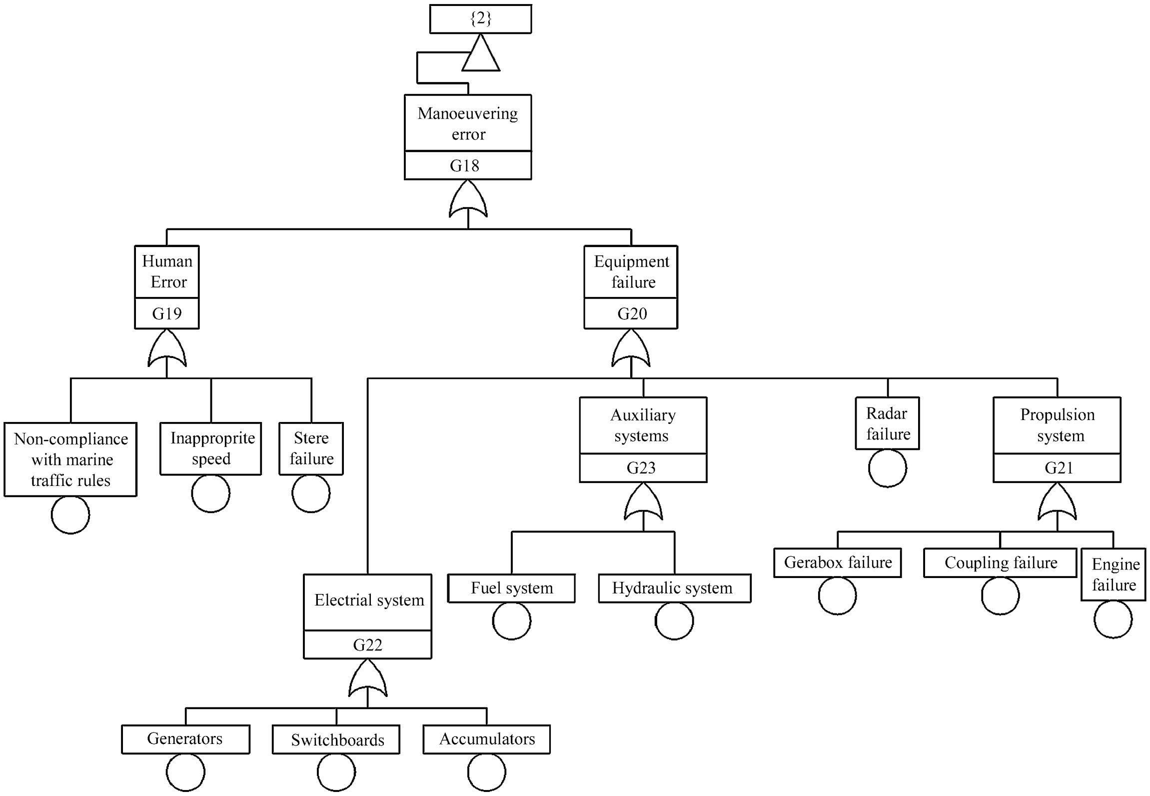

Fig. 3 Developed fault tree (continued)

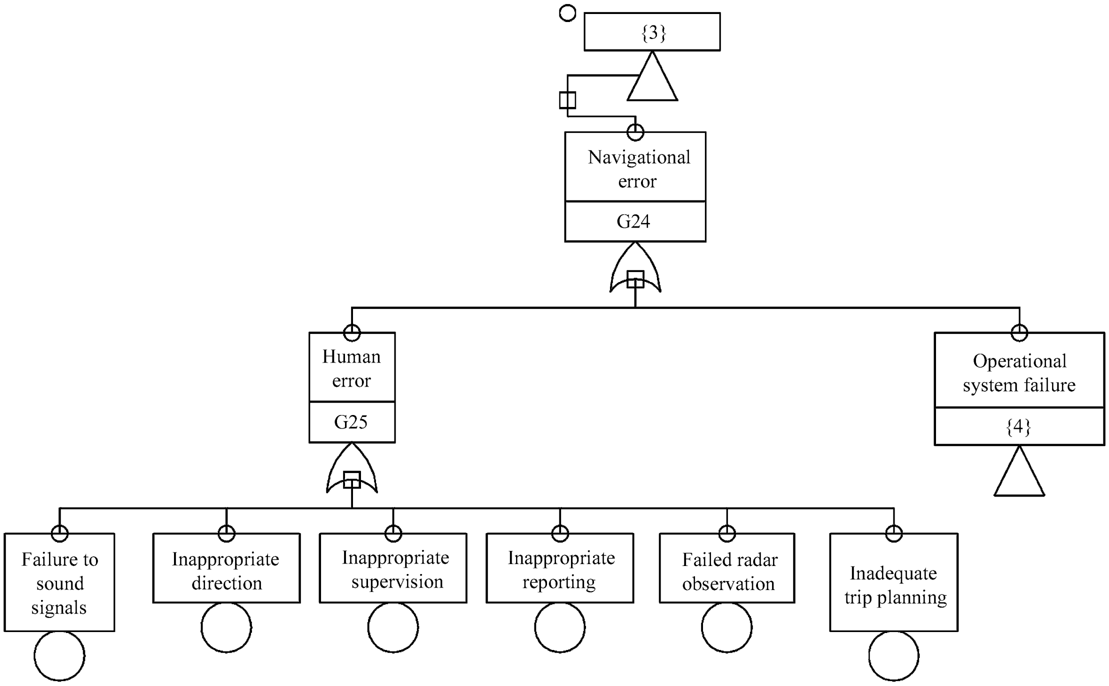

Fig. 4 Developed fault tree (continued)

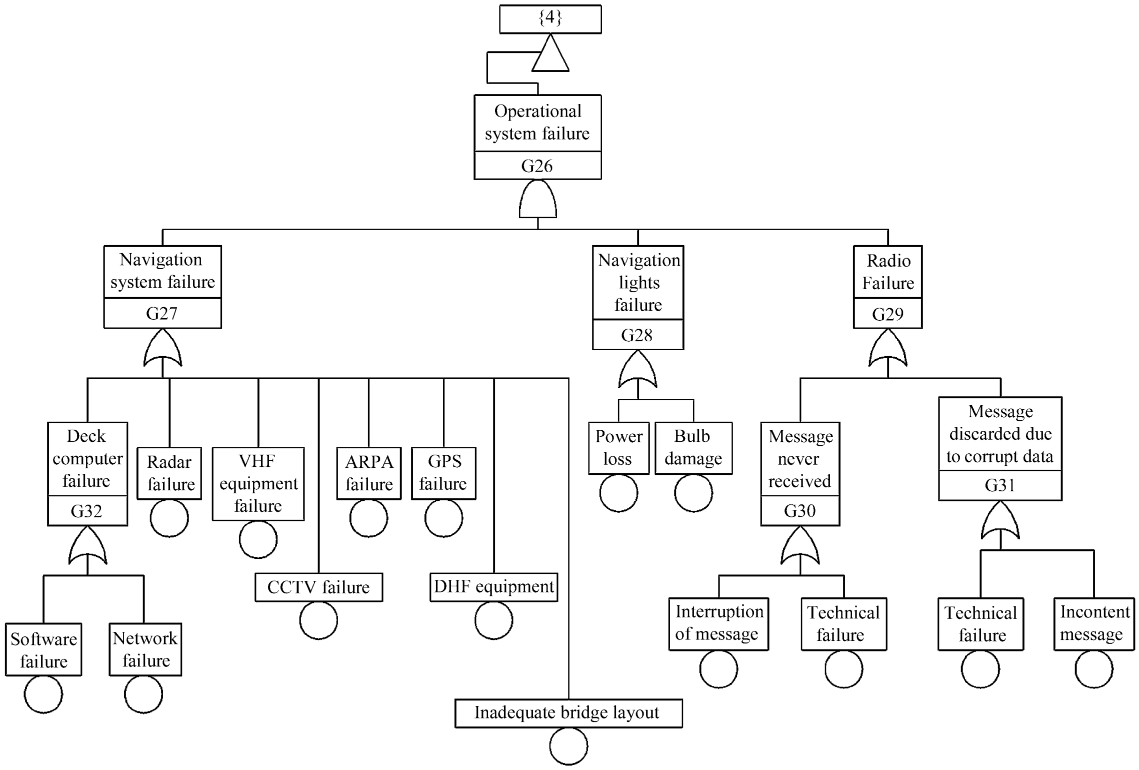

Fig. 5 Developed fault tree (continued)

ification of the cut sets related with design issues and human factors related to each accident case.

Obviously the unavailability of data has affected the degree of uncertainty of the analysis. After the fault tree is built, an important step in the Fault Tree exploitation is to search all the basic event combinations, a step which is both a necessary and sufficient condition in the occurrence of the Top Event. These combinations are known as Minimal Cut Sets (MCS).

If one of the events in one MCS does not occur, the Top Event will not occur. Having built the fault trees for the several casualty events, the next step is the identification of the MCS for each of the events. As expressed above, the software allows the automatic identification of the several cut sets. The outcome resulted in a series of combinations of the different basic events with dimensions depending on the complexity of the fault tree under analysis.

For the collision fault tree, a quantitative analysis was performed to determine the minimum cut sets with Boolean algebra. From the analysis, 150 cut sets were found. More specifically, a total of 18 cut sets of single order events leading to the main event with a probability of 1.0E−3 were found. However, only 2 cut sets of second order with a maximum probability of 9.51E−7 were found. Many of the cut set combinations were related to human errors or inadequate management procedures. However, special attention was given to minimal cut sets involving design issues.

Table 2 is a summary of the failure modes with higher failure probabilities or with higher contributions to the casualty event. On the left side of the table are the design failure modes that were by themselves minimum cut sets. On the right side of the table are the failure modes that have a lower probability for the emergency scenario, but also have frequent representation in several cut sets.

Table 2 Design related cut set factors

Radar failure	Lack of on-board collision avoidance system
Propulsion Failure	
Steering failure	VHF equipment failure
Steer failure	Power loss
Engine failure	CCTV failure
Gearbox failure	ARPA failure
Coupling failure	GPS failure
Generators	DHF equipment
Switchboards	
Accumulators	
Fuel system	
Hydraulic system	

Grounding can be seen as the deliberate contact by a ship with the bottom while she is moored or anchored as a result of the water level dropping. The grounding of ships is generally subdivided into power groundings, when the ship hits the obstacle with large velocity and drift groundings, when the vessel hits the obstacle while drifting with small velocity. The drift rate of the ship mainly depends on current, wave, and wind data. Coastal waters factors like the possibility of tug escort and emergency anchoring must be taken into account in the analysis.

Power groundings can be considered as collisions with a fixed obstacle and the same parameters as described above for ship-ship collisions will be used to determine the basic events related to this type of casualty occurrence. Vessels of high speeds are particularly endangered when grounding occurs. From statistical analysis of the existing maritime agencies worldwide, one may see that most of the causes identified were related to human factor issues like dozing, non-confirmation of vessel position, or poor selection and maintenance of course. These human related causes, together with design contributors such as radar, engine and steering failures, and poor bridge layout, increase the probability of grounding. In terms of consequence contributors factors such as fire, rough weather, inadequate structural design, and poor visibility can increase the outcome in terms of vessel damage or casualties to the passengers and crew.

In general, the consequences of groundings are conveniently subdivided into two categories, similar as for collision: (i) the direct damage to the ship hull due to the grounding impact, and (ii) the subsequent damages like flooding and possible capsize, fire, machinery failures, and possible loss of life. From the analysis of the grounding FTA cut sets, 109 cut sets were found. More specifically, a total of 40 cut sets of single order events leading to the main event with a probability of 9.95E^{-3} were found. These single order events were related with human factor and basic events associated with navigational tasks on the bridge. Also found were events related to navigational equipment failures including faults with the steering, hydraulic, and propulsion systems.

In terms of consequences, capsize can be the most dangerous accident. Collision between ships, followed by flooding, often occurs at sea. Most ship types, when flooded, sustain a gradual increase in draught, trim and/or heel, culminating in foundering or capsizing. Capsizing is a phenomenon by which the ship turns upside-down, attaining heel angles in excess of 90°. It may be caused by flooding or other causes and can represent the last stage of a foundering process. Ro-Ro ships present a tendency to capsize after sustaining considerable flooding damage. Therefore, it includes the damage inflicted by other ships, but also the openings caused by operational faults or mechanical breakdowns.

The most dangerous is the loss of stability on the wave[8]. The vessel spends a longer duration on the wave crest than in the wave trough due to the non-linear nature of periodic surging motion with potential surf-riding equilibrium. During the duration on a wave crest, the righting arm of a ship could decrease significantly. In the case of pure following seas, for instance the heading angle of zero degrees, a ship could capsize simply due to loss of static balance by a reduction of transverse stability. This phenomenon is known as pure loss of stability. If the heading angle is changed to stern quartering seas, the ship suffers both reduction of the restoring arm on a wave crest and the wave exciting roll moment. Here a dynamically coupled sway-yaw-roll motion becomes significant and can cause a capsize on a wave crest. This cannot be named as 'pure loss' because of a significant dynamic motion before capsizing. Due to the fact that Ro-Ro and RoPax vessels do have a barge type aftbody and a semi-submerged transom, they lose much of their initial stability on the wave crest, therefore, these vessels are vulnerable to parametric rolling[9].

Although it is difficult to fit Ro-Ro accidents into predefined patterns, Dand[10] categorises the capsizing of damaged Ro-Ro vessels into two broad types: speed-induced and drift-induced. Spouge[11] makes a similar distinction, but without attributing much importance to speed as the major cause of the first accident type. In the first type, the forward speed of the ship causes large quantities of water to be taken on board very rapidly through the damaged opening. When, for example a RoPax ferry is hit by a vessel with a bulbous bow, damage will occur to the side shell of the struck vessel[12]. This damage may look similar to the one observed when the Ro-Ro vessel European Gateway was struck by the Ro-Ro vessel Speedlink Vanguard. It is worthy to note that due to the complexity of the capsize fault trees, a minimum of 1024 cut sets were found. This result is understandable when it was considered in a fault tree of nearly 140 basic events. From the analysis of the minimum cut sets, these were mainly related with the dynamic aspects of the vessel, in particular to the stability. Failure of the dynamic system, anti-heeling tanks, and trim pumps, compensated for the loss of stability or due to design inadequacies, asymmetric flooding, internal subdivision, stability design can force the vessel into a rapid capsize. These results are in agreement with the conclusions of the work performed by Santos *et al.*[13] where it was highlighted that the potential for an accident, if transient heel, occurs due to the accumulation of water in a flooded compartment as a result of obstructions to the water flow.

Fire is a major risk for passenger ships. It is not negligible occurrence whose consequences may well be dramatic. Similarly to the risk involved, the potential costs of a fire spreading outside the space of origin can be enormous. Although their frequency of occurrence is relatively low in passenger ships, several accidents have occurred in previous years with far reaching consequences from which the Scandinavian Star is the ultimate case. As expressed by IMO, "fire also represents a particular vulnerability for large cruise ships and every passenger is a potential ignition source and the hotel services have an inherent risk". In the case of RoPax this statement is also true with the addition of the potential existence of dangerous goods on board. These dangerous goods typically are placed on the stern of the vessel in an open deck in order to allow a rapid response of fire combat tugs in case of a fire.

Fire can be seen as any condition involving evidence of fire, smoke, or an impending explosion. This would include the sighting of smoke or fire, odorous evidence of burning, or concentrations of flammable gases. The fire triangle consists of fuel, oxygen and heat. All three must be present to start a fire and the removal of any single one can extinguish a fire. Fuels, such as gasoline and propane, can be very dangerous if precautions are not taken. The smokes of these fuels are heavier than air and tend to collect in the cabin, bilge and other lower areas of the vessel. Small leakage of these fuels in the engine rooms is frequent, increasing the probability of an accident. Possible relationships for the collision variables expressed in the analysis are illustrated in Table 3.

Table 3 Accidental events/loads for fire accident

Cause contributors	Consequence contributors
Rough weather	Explosion
Flammable cargo	Fire
Electrical failure	Flooding
Oil leak in fuel and hydraulic systems	Water pumped on board
	Heeling
Heeling	Grounding
Cargo shift	Fire alarm failure
Bomb	Fire door failure
Arson	Engine failure
Sparkling or welding	Power failure
	Steering failure
	Smoke spreading
	Capsizing
	Inadequate passive and active fire systems
	Inadequate ventilation type

In terms of consequence contributors, ventilation is an important aspect since it influences the supply of oxygen to the fire and the spread of toxic gases around the different compartments. Both natural ventilation, under doors or through vents, and mechanical ventilation, extractor fans are key elements as they determine the speed in which the fire can spread. Also, the rapid response of the crew to a possible evacuation of the passengers along with the reliability of the fire protection equipment, sprinkler systems, smoke detectors and fire doors will decrease the outcome of such event.

4 Sensitivity analysis

In order to assess the sensitivity of the fault trees to some of the most important basic event probabilities of the set of variables, a sensitivity analysis was performed. Therefore, for each of the accidental events, a variation of the human factors basic events that presented a higher contribution for the probability of the main event was changed systematically. In Fig. 6 to Fig. 9 are the results of the variances of the probabilities of the main events when changing both the human factors initial probabilities and the main contributor system for each of the terminal events.

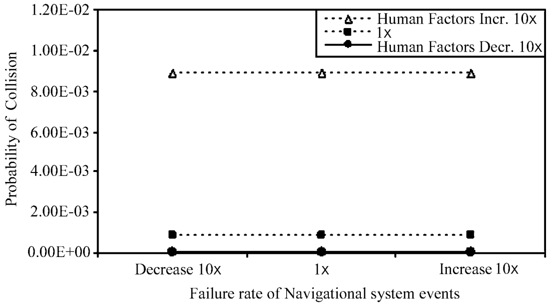

Fig. 6 Variance of probability of Collision

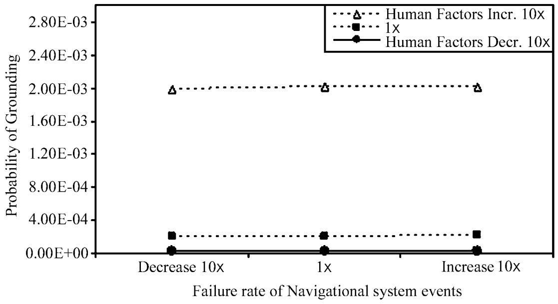

Fig. 7 Variance of probability of Grounding

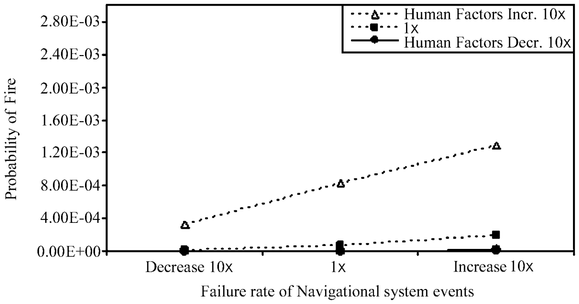

Fig. 8 Variance of probability of Fire/Explosion

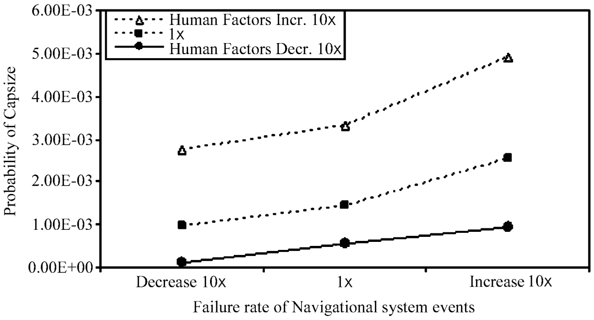

Fig. 9 Variance of probability of Capsize

From the analysis, one may see that when the human factors basic events are changed, the effects on the probabilities factors of collision and grounding change significantly. For an increase in the order of 10 in relation to the initial probability of the basic events, it obtained a variation of almost 90% in the case of the collision and of 80% for the grounding. Similar results occurred when the human factors basic events probabilities are decreased in the same magnitude. When the probability of navigational system basic event probabilities decreased, almost non significant, variances occurred to the probabilities of the terminal events, changing in the order of 1% for collisions on 3% for groundings. This leads to the conclusion that, although there are several cut sets of failure of equipment, the human factors basic events are highly dominant in these two types of accidents.

For the cases of the fire/explosion and capsize, this effect is less significant. If the probability of human errors basic events is decreased by 10, the probability of capsize will decrease 50%, for instance, a reduction from 8.86E−4 to 1.09E−4. In the case of fire the reduction will be of 70% in the probability, for example a reduction from 1.86E−5 to 1.26E−6. However, on these cases involving a change on the stability system basic events, capsize, and fire control systems and, for the cases of fire/explosion, corresponds to a variation of almost 80%; in some of the changes, for the capsize, and 34% for the fire/explosion. This consistently high dependency of human errors for the case of fire/explosion, although most of the basic events are related to equipment failures, can be explained by the fact that most of these human errors are first order minimal cut sets. Since the probability of the top event is highly dependent on the first order minimal cut sets the human errors have a higher contribution to the probability.

5 Conclusions

The main objective of this study was to establish propagation rules over a network/tree of elementary ship system failure modes in probabilistic terms with the development of a framework for overall performance assessment in terms of Availability, Operability, and Survivability. The investigation of the failure modes under various emergency scenarios was performed, namely: fire/explosion, collision, grounding, and capsizes. The study was performed by using FTA in order to assess the safety performance of a RoPax vessel. This was achieved by determining the combination of the different minimum cut sets associated with each of the emergency scenarios under analysis. From the fault tree and subsequent sensitivity analysis, one may see that the basic events related to human factors are the dominant factors towards the accidental event. This contribution is higher for groundings and collisions where an increase of the initial probability leads to a change of almost 90% in the probability of the occurrence of these terminal events. In the cases of the fire and capsize this effect is less significant.

Acknowlegments

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