NATIONAL TECHNICAL UNIVERSITY OF ATHENS

SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING

***DIPLOMA THESIS*:**

"ANALYSIS OF NON ACCIDENTAL STRUCTURAL FAILURES ON ROPAX VESSELS"

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ABBREVIATIONS

DNV	Det Norske Veritas
EMCT	European Conference of Ministers of Transport
ETA	Event Tree Analysis
FSA	Formal Safety Assessment
GT	Gross Tonnage
HAZID	Hazard Identification
HRA	Human Reliability Analysis
IACS	International Association of Classification Societies
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
LCRs	Loyds Casualty Reports
LFRP	Loyds Register Fairplay casualty database
LMIS	Loyds Maritime Information Services
LNG	Liquefied Natural Gas
LOWI	Loss of Watertight Integrity
LSA	Life Saving Appliances
NASF	Non Accidental Structural Failures
PDP	Potential Damage to Property
PEI	Potential Environmental Impact
PLL	Potential Loss of Life
PRA	Probabilistic Risk Assessment
RCO	Risk Control Options
RMA	Radioactive Materials
RoPax	Roll-on-Roll-off Passenger Ships
SOLAS	Safety of Life at Sea
SSS	Short Sea Shipping
THERP	The Human Error Rates Prediction

ABSTRACT

The specific study represents the outcomes of a Statistical and Risk Analysis for RoPax ships, performed for incidents which occurred in 1985-2016 without concerning for each ship's year of built while their initial cause was a Non Accidental Structural Failure (NASF).

Initially, the scope of the thesis is explicitly stated so as to acquire knowledge for the reasons of the occurrence of such study (Chapter1). In the next section (Chapter 2), other investigations and studies which have already used Event Trees as basic tool are mentioned. Moreover, general information about RoPax ships, types of NASF and the process that was followed during this research is presented (Chapter 3). A high level statistical analysis with respect to all kind of incidents occurred (Chapter 4) and a detailed statistical analysis which concerned only incidents with NASF was performed too (Chapter 5). Risk Analysis with regards to NASF (Chapter 6) that had been recorded by the database was the basic aim of this thesis while the comparison of those incidents as far as their consequences concerned with theoretical values that derived by the implementation of Monte Carlo simulation was the other significant issue of this analysis (Chapter 7). Conclusions (Chapter 8) for the emerging results were drawn and some ideas for future work (Chapter 9) which could be taken into consideration so as to contribute in further studies are expressed at the end of this research.

ΠΕΡΙΛΗΨΗ

Η συγκεκριμένη διπλωματική εργασία πραγματεύεται την ανάλυση ατυχημάτων πλοίων τύπου Ε/Γ- Ο/Γ. Πιο συγκεκριμένα, παρουσιάζεται μία Στατιστική ανάλυση και μία ανάλυση Ρίσκου σε ατυχήματα που προκλήθηκαν λόγω δομικών αστοχιών σε πλοία του προαναφερθέντος τύπου και έλαβαν χώρα κατά τη χρονική περίοδο 1985-2016.

Αρχικά, ο σκοπός της εργασίας υποδηλώνεται ώστε να γίνουν αντιληπτοί οι λόγοι που οδήγησαν στην εκπόνηση της συγκεκριμένης εργασίας (Κεφάλαιο 1). Στο επόμενο κομμάτι, αναφέρονται κάποιες άλλες έρευνες που είχαν ήδη χρησιμοποιήσει τα Δέντρα πιθανοτήτων ως βασικό εργαλείο (Κεφάλαιο 2). Επιπλέον, γενικές πληροφορίες για τα Ε/Γ- Ο/Γ πλοία, τα είδη των δομικών αστοχιών αλλά και για τη διαδικασία που ακολουθήθηκε για την εκπόνηση της εργασίας είναι ορατές (Κεφάλαιο 3). Στατιστική ανάλυση για όλους τους τύπους των ατυχημάτων (Κεφάλαιο 4) και μία λεπτομερή στατιστική ανάλυση που αφορούσε μόνο τα ατυχήματα δομικών αστοχιών πραγματοποιήθηκαν στη συνέχεια της εργασίας (Κεφάλαιο 5). Στη συνέχεια, εφαρμόστηκε ανάλυση Ρίσκου στα ατυχήματα που προήλθαν από δομικές αστοχίες και ήταν καταγεγραμμένα στην εξεταζόμενη βάση δεδομένων (Κεφάλαιο 6), ενώ η εφαρμογή του Monte Carlo Simulation επιλέχθηκε ώστε να καταστεί δυνατή μία σύγκριση των θεωρητικών δεδομένων των συνεπειών που μπορούν να προκληθούν από ένα ατύχημα δομικής αστοχίας για όλο το στόλο των Ε/Γ- Ο/Γ ανεξαρτήτου ατυχήματος, με τις τιμές των συνεπειών που προέκυψαν από τα υπάρχοντα ατυχήματα (Κεφάλαιο 7). Συμπεράσματα που προήλθαν από την ολοκλήρωση του υπολογιστικού κομματιού (Κεφάλαιο 8) και προτάσεις για μελλοντική έρευνα (Κεφάλαιο 9) παρουσιάζονται στο τελικό μέρος της εργασίας.

1. Introduction

1.1 Preface

Shipping has already been recognized as one of the strong catalysts for social and economic development because of its vital role in worldwide trade. From the ancient years, humans tried to explore and use sea for reaching to their destinations easily and in the minor time period (Richard Woodman, 1998). But because of the incomplete knowledge and uncertainties such as the weather, plenty of these efforts led to significant accidents with severe impacts on the environment and the human life. No one can deny that nowadays these unexpected and harmful situations continue to happen and it is crucial to be researched for the further comprehension of the causes and the consequences of the casualties.

There are 6 main categories of marine accidents that can be distinguished and are presented below:

- Collision
- Contact
- Fire/ Explosion
- Foundering
- Hull/Machinery Damage
- Stranded/ Wrecked

Most of them occur during an operation and due to the human factor. Some reasons that contribute to the creation of a casualty are the unsatisfactory training of the crew, the inadequate cartography of dangerous and unknown areas and the conditions that a voyage is taken place. These reasons can be predicted and prevented with the assistance of experts who would help the crew to be well-trained and inform them for climate changes.

Another imperative cause of a marine incident is the Non Accidental Structural Failure (NASF) which cannot usually be faced by the crew during the voyage and may engender essential results for an accident.

1.2 Scope of the thesis

The issue of present thesis is the statistical and risk analysis of the Non Accidental Structural Failure (NASF) that occurs in hull, tanks and pipes of RoPax ships. This research was held with the restriction of the time period that casualties happened, as the incidents that are studied, occurred in 1985-2016 independently of the year of built.

The aim of this study is to analyse existing historical data for NASF in RoPax fleet so as to establish risk contribution diagrams (Event Trees) based upon the casualty data and estimate or evaluate risk of RoPax for the specific accident categories by each size either with the Event Trees or by Monte Carlo Simulation. Also, this study attempts to estimate the risk of loss of life among passengers and crew onboard RoPax ships and the risk of the environmental impact by calculating the possibility for each identified scenario. Furthermore, potential cost to the property, after the occurrence of any of the investigated potential scenarios, is attempted although that this can vary due to different conditions of an accident.

2. Literature Review

This section presents a brief and solid historical background of previous studies which occurred by the worldwide community with topics related to the elaborated analysis. It must also be remarked that all these studies are related to marine operations.

Because of the consequences that are derived by oil spill and the magnitude of the outcomes, an innovative research was held in *1997* by Amrozowicz, Brown and Golay. Their study was focused on tanker ships which had suffered grounding as tankers had until then the biggest contribution in USA's oil spills and the most frequent polluting casualties had been derived by grounding. The purpose of current study was to identify and analyse risks that had existed with respect to the human errors. In current analysis, data for ships was taken by the CASMAIN database for the period of 1981-1991 and were examined so as a Probabilistic Risk Assessment (PRA) to occur with the aid of Fault and Event Trees. Also, it must be remarked the fact that similarly to PRA, Human Reliability Analysis (HRA) was conducted by the means of Human Error Rates Prediction (THERP).

Two main events were distinguished for the creation of Event Trees and Fault Trees that were related to the human error. The former was defined as Powered Grounding and this term had been referring to tankers that had collided with the shore due to navigational errors or lack of crew's awareness. While the latter was named Drift Grounding and it was related to the loss of ship's steering or propulsion with the result of the grounding onto a shore. For each case, fault trees were developed at first, for the identification of risk and subsequently Event Trees were shown so as to quantify the probabilities and the causes of accident scenarios for determining the performance of human reliability. Powered Grounding was separated to two other causes, passage planning and piloting, so a better analysis to occur whereas Drift Grounding was studied as an entity. For those three factors failure probabilities and trees were developed and data of the four busiest ports were used so as to be found accident quotients and compare them with the probabilities that emerged because failure were dependent on the time of transit and transit length.

A perceivable result of current research was the calculation of the probability of grounding depending on time of near-shore transit as the sum of Powered and Drift Groundings failure probabilities. Furthermore, it was comprehended that human factor plays a significant role to the incidents of Grounding and as a consequence to the spread of oil. Eventually, it emerged that basic skills of seamanship are the most critical to the tanker's safety as human reliability can limit the faulty planning and piloting whereas the time of response in case of ship's losing the ability of navigation could be diminished if crew and other authorities are in vigilance.

In *2001* occurred a research by the International Atomic Energy Agency (IAEA) which title was "Severity, probability and risk of accidents during maritime transport of radioactive material". The participants of current study were from five countries and the whole study lasted about five years. The aim of this research was the existing regulations for ships which transferred radioactive materials (RMA) to be examined with respect to the frequencies, probabilities and outcomes of these ships' accidents.

For the occurrence of the study, a period of 15 years (1979-1993) was taken into consideration and serious accidents of ships with RMA complied with Safety of Life at Sea (SOLAS) regulations and requirements for ships with RMA (INF code) were taken by Lloyd's and MAIB's database. Containerships, general cargos, Ro-Ro and RoPax ships were considered as the appropriate ones in the study. Serious accidents considered those which caused injuries, deaths or total loss of the ship.

Initially, statistical investigation occurred in relation to collision and fire incidents and except for probabilities, frequencies were calculated too. Subsequently, risk assessment was taken place with regards to the fire in engine room. So, Event Trees for the internal fire were developed so as the possibilities of preventing the fire to have been calculated. Finally, statistical data in relation to other different accidents, e.g. foundering or wrecked, had presented.

Conclusions of this study were that the release of a radioactive material to the atmosphere could expose humans to radiation after a collision accident which would initiate severe fire. In any other occasion, the risk of transporting RAM to cause radiation doses would be very small.

At the same year, *2001*, the summary of the Formal Safety Assessment (FSA) for bulk carriers with respect to Life Saving Appliances (LSA) had published too. Det Norske Veritas (DNV) in co-operation with other Norwegian authorities submitted current research to International Maritime Investigation (IMO). Its target was to summarize the outcomes of the investigation that had been done for LSA's bulk carriers.

There were presented details with regard to the procedure that FSA was performed. The investigation had occurred accidents which occurred in SOLAS Bulk Carriers with length at most eight-five meters for the period 1991-1998 that had been taken by Lloyds Maritime Information Services (LMIS) and Lloyds Casualty Reports (LCRs) database. First step of the research was the hazard identification for each type of lifeboats that had been distinguished. It must be remarked that four types of survival crafts were considered. The second step included Risk Assessment and the development of Event Trees with respect to evacuation procedures and lifeboat types. Event Trees were independent of accident scenarios and was formed in binary type. As outcomes of Event Trees were considered the Potential Losses of Life (PLL) and comparisons for each type of accidents were described in relation to probabilities of the fatalities. Third step contained the identification of Risk Control Options (RCO) while fourth step Cost Benefit Assessment estimated the costs and the benefits of the implementation of RCO. Finally, in the last step some recommendations with regard to the predefined RCO had been proposed.

The significance of this research was that useful outcomes with regard to the LSA of bulk carriers had emerged and RCO had identified so as improvements to that field had become feasible.

Approximately, one year after, in *2002*, Shipbuilding Research Association of Japan conducted an FSA study for bulk carriers with respect to the water ingress to cargo holds and the structural failures of current ships. It must be remarked that the research was based on the five steps of the FSA and the historical data for accidents that occurred during 1978-2000 was taken by LMIS casualty database.

The first step was the implementation of the Hazard Identification (HAZID) so as hazards to be recognized with regard to the database and frequency and severity indexes to be calculated for the estimation of risk matrix. Also, fault trees in relation to structural failures and loss of ships was taken place in specific step. Continually, the second step, which was the Risk Analysis, contributed to the quantification of the risk for each predefined scenario by HAZID. So, Event Trees were developed for bulk carrier with 10.000DWT or more and casualties that their failure initiated from a hatch cover or hull structural failures. Fatalities, frequencies of casualties, PLLs and fault tree analysis with respect to ship's total loss due to flooding were observed too. The third step was the presentation of predefined RCO by HAZID and the identification of new ones that emerged due to the inadequate safety. Moreover, factors which led to risk reduction and measures for their implementation were proposed. Another aspect of this research (Step 4) was the evaluation of the cost effectiveness with regard to the RCO and the estimation of the economic benefits from the application of RCO. Values for economic losses for a serious casualty and for ship's total loss were given too. The last part of current study (Step 5) recommended some actions with regard to the effects of the study so as the safety on bulk carriers to be enhanced.

Goals of this research were the investigation of the hazards and risks that had existed during the bulk carriers' operation and the definition of measures with respect to the cost effectiveness for safety's improvement. Quantification of risk values and frequencies for specific types of accidents were presented as well. Because of the significance of an FSA study, similar studies for other ships' types were held too in the next years. In 2007, two researches with regard to FSA had occurred, one for containerships and one for Liquefied Natural Gas (LNG) ships. In 2008, tankers, RoPax and Cruise ships were studied too, while general cargo ships were taken into consideration in an FSA study in 2010.

Using information which had been taken by (DNV Technica 1996a) study with regard to the safety assessment on RoPAx ships that had been sailing in North West European Sea during 1978-1996, risk evaluation criteria by Safedor project (Safedor 2005) and data by Lloyds Register Fairplay (LFRP) casualty database, a report which was part of Safedor project was published in *2008* with authors Konovessis, Vassalos and Mermiris. Aim of this paper was to estimate the risk of loss of life and recommend improvements by the developed risk model on RoPax ships for the period 1994-2004.

First of all, some information in relation to the worldwide RoPax fleet for predefined period were given, risk criteria for people onboard a RoPax and hazards that could have existed on specific category of ships were presented. Current paper took into consideration two categories of RoPax vessels that had complied with SOLAS, ships of 1000 to 4000GRT and 4000GRT and above, for the casualty analysis. Moreover, not only frequencies and probabilities of accidents for these two categories of RoPax vessels had been assessed for all types of accidents but comparisons with the previous study (DNV Technica, 1996) was held too. Furthermore, a risk model was developed for five types of accidents (collisions, groundings, impacts, other flooding and fire) and for all fleet of 1000 GRT and above with the aim of estimating fatalities, Potential Loss of Life (PLL) and frequencies for each type of casualty. Also**,** Event trees were developed for every specified category of accidents so as to fulfill the risk model. Eventually, risk control options of IMO had described.

As a result, conclusions about the accidents of RoPax fleet for the period of 1994-2004 and their fatalities and frequencies became obvious and the enhancement of the safety emerged by the comparison with results of the previous survey on similar vessels in the period 1978-1996. Finally, having presented hazards and risk control options, the conclusion that the risk was still high, was more than valid.

In a research that was coordinated by VTT Technical Research Centre of Finland in *2009*, the survivability of ships in case of fire was studied. The specific study was developed in four sections which concerned materials, hazards, structures and the evacuation.

For the first section, materials and products that had been used in shipbuilding were examined via tests with respect to their performance levels during a fire. As far as hazards' section concerned, information and models about the Fire Safety Engineering process were given so as the significance of smoke detectors, automatic fire suppressions and other design issues to be presented and everyone understand that design is the first solution for the prevention of a fire. Presenting other studies for the fire such as the aforementioned IAEA research and Det Norske Veritas (DNV) fire statistics from 1992-2004 statistics for fire had been given. But the issue that had been taken into consideration a lot in this study was a cabin fire on a passenger ship. Scenarios were developed due to the GISIS database of IMO and a quantitative risk analysis for a passenger ship cabin occurred. Because of the Event Trees, probabilities of a fire or explosion in a cabin with regards to its significance and its progression had become obvious to everyone. Also, with time-dependent event trees the period of the spread of a fire became feasible. Therefore, for structures chapter an engine room fire below a car deck was examined so as a thermal analysis with respect to the nature of ship's structure to occur. Finally, current research had described the evacuation simulation model of FDS+Evac for ships that was developed taking into account different kind of staircases, the possibility of lost passengers and the training of the crew.

The outcomes of specific study were quite interesting because reasons of the fire emerged, risk analysis determined the probability of fire to spread outside the cabin and evacuation scenarios were analysed.

Some years after, in *2013*, Papanikolaou et al published a paper related to a project which was conducted at the period 2009-2012. Its aim was to present the outcomes of the project which had enhanced the safety of the maritime passenger transport and they had developed some risk-based procedures with the simultaneously occurrence of tests for the survivability of passenger and cruise ships.

Firstly, on the basis of HARDER and IHS Fairplay databases, damage statistics with regard to collision and grounding accidents for all ship types and for the period 1944-2009 were developed. Having taken into consideration the capsize phenomenon and the water on deck problem, a new probabilistic survival factor, known as s-factor, was calculated for hull damages on passenger ships. Moreover, studies onto four ship models, two RoPax and two cruise ships, provided information on passenger ships with regard to the stability of specific ships during a hull breach after collision and grounding casualties. Also, risk models for cruise and RoPax ships that had involved in grounding and collision incidents during 1994-2010 were conducted with respect to SAFEDOR FSA guidelines. So, four Event Trees were developed for these two types of accidents for the concerned categories of ships. For each scenario and event of the trees, risk control options and a cost benefit analysis were taken place. Eventually, six models of passenger vessels with innovative designs were optimized, meeting the developed damage stability requirements, operation’s efficiency and the costs so as the definition of subdivision index and cost effectiveness analysis to be performed.

The results of current project were quite significant and useful for the passenger ships. A new probability of survival of hull damages on passenger ships was estimated, new stability standards for grounding and collision casualties were implemented with experimental studies and calculations of cost effectiveness for plenty risk control options became. Also, updated types of passenger vessels based on the presumed requirements proposed and outcomes of their tests were presented.

3. General Information

3.1 Definition

Ropax is an acronym that its meaning is Roll-on-Roll-off-Passenger-ship.

RoPax ships are vessels that include RoRo capabilities (carriage of private vehicles, commercial vehicles, trucks, trains and other types of cargo) with the addition of space for the accommodation for at least 12 passengers (SOLAS definition).

Figure 3.1: Typical Greek RoPax

3.2 Background

RoPax is classified as short sea shipping (SSS) mode of transport. SSS are often considered as environmentally friendly due to a reduction of traffic congestion, air pollution, noise and road damage. SSS may be considered as competitive for the other means of transport but actually sometimes complements and enables other modes of transport depending on geographic dependencies and current regional infrastructure (ECMT, 2001). Because of the variety of cargos that a RoPax carries, additional technical and passenger safety requirements are imposed. It is significant to be mentioned that by this kind of ship a lot of people are transferred so an additional attention must be given during the construction and the operation of this ship.

It is known that RoPax are widely used and sailing in huge variety of operational areas. As a result, these ships exist in many sizes depending on the purpose that want to serve and the necessities of each region that they would be established. Maritime community has separated specific ships to 3 categories, which are listed below:

- 0-1,000 GT that are usually ships engaged on short crossings and the passages are often of an open type configuration.
- 1,000-4,000 GT which ships are committed to medium distances and the transportation of a large number of passengers
- 4,000 GT and above that are consisted of vessels that make medium and large voyages with high capacity of passengers

There was always the tendency in the worldwide market to build new larger ships with more options for faster loading and unloading, despite the classes and the big amount of ships that had already existed. Moreover, RoPax vessels are responsible for the people's and vehicles' transfer. It is an undisputed fact that the approach to some destinations can only happen by the sea or by the air which in many occasions is very expensive or undeveloped. Such demands in size and concept led to new designs and innovative methods of construction to be held with the prospective of a lucrative business (Anthony F. Molland, 2008). However, plenty of these efforts were spoiled due to the orientation that profit is the only concern regardless of the safety of the crew or ship's passenger.

Nowadays, the necessity for a safer and an easier-operational ship for the crew have been realized by ship owners, the global community and some organizations which create safety regulations and inspect which companies are not in compliance with the restrictions that are widely accepted. So many regulations have been developed for every type of ship and as a result for RoPax ships by the International Maritime Organization (IMO). IMO demands an adequate number of measures that a vessel must be compatible so as to be capable of operating a voyage. Amendments and improvements of restrictions usually occur after a big accident, that experts perceive that current regulations are not adequate, with the scope of enhancing all the more the safety of the passengers but also prevent pollution of environment. As a consequence, it is obvious that analysis of incident's causes and statistical analysis for past incidents with regards to the consequences are vital for the prevention of additional and more harmful casualties.

3.3 Specification of the considered Incidents

As it has already mentioned, RoPax ships belong to a category of ships that their cargo is quite important provided that people could consider as a kind of cargo. So, every shipping company which is involved in current industry should have as its first priority passenger's safety.

While a large number of studies focus on the investigation of accidents which directly derived by the human error or the wrong mapping of global area such as collisions, this thesis attempts to highlight the significance of the impacts that engender by Non Accidental Structural Failures (NASF) and it is quite difficult to be located or predicted by humans.

NASF contain dents, cracks and other local failures of vessels' hulls which are usually created by fatigue. Another main cause of NASF is the corrosion of some spots of the ship which either come in contact with the corrosive environment of the sea or are not maintained on regular periods.

The two main causes of a Non Accidental Structural Failure are presented below:

3.3.1Corrosion

Generally, corrosion is a natural procedure in which a refined metal is deteriorated due to chemical or electrochemical reactions to its surrounding environment. The grade of metal's destruction depends on the nature of the using metal and the environmental conditions (e.g. temperature, oxygen). The electrochemical theory of corrosion is based on the fact that the exposure of an iron does not cause corrosion. The electrochemical reactions that describe current effect are presented below:

Anode: $Fe\,(s) \leftrightarrow Fe^{+2} + 2\,e^{-1}$

Cathode: $\frac{1}{2}\,O_{2(g)} + H_2\,O_{(l)} + 2\,e^{-1} \leftrightarrow 2\,OH^{-1}$

(neutral sol.)

Cathode: $2\,H^{+1} + 2\,e^{-1} \leftrightarrow H_{2(g)}$

(acidic sol.)

So, the overall reaction of corrosion can be derived and its equation is:

$$Fe_{(s)} + \frac{1}{2}\,O_{2(g)} + H_2\,O_{(l)} \leftrightarrow Fe(OH)_{2(s)}$$

In the marine environment, where is characterized by salt water and humidity, corrosion of the hull is unavoidable and plays a significant role to the economic life of a ship as the material thickness is decreased and consequently the strength of structure is reduced (Kenneth A. Chandler, 1985). Also, in some occasions it is observed corrosion to tanks, especially in their coating, and in pipes.

The hull, tanks and pipes being continuously exposed to the corrosive environment can be suffered by a lot of different kinds of corrosion. The most frequent ones are presented below:

- **Galvanic corrosion:** It is the most dangerous form of corrosion in ships as it occurs because of the presence of an electrolyte such as salt water and the contact of two or more different metals. The one metal, which is characterized as anode, corrodes more quickly as its ions move to the other (cathode). However, sometimes the existence of two different metals for the occurrence of a galvanic corrosion in ship’s hull is not necessary. For example, in the case of the plates that are consisted of flanges, those functioned as anodic to the rest of the plated owing to the fact that stress is limited to the flange.
- **Stress Corrosion Cracking:** It is a hazardous type of corrosion in which a majority of tiny cracks due to tensile stress are developed and they cannot be easily seen. It leads to a rapid failure.
- **Crevice Corrosion:** It refers to the interaction of a metal surface with two environments that are joined or connected. The result of current corrosion is a gap or a crevice between the two connected environments.

Figure 3.2: Crevice corrosion

- **Flow-Accelerated Corrosion:** It is derived by the constant flow of water and it is observed in metal surfaces that come in contact with water. Spots that it is possible this type of corrosion to be found are bends and elbows of pipes.
- **Inter-granular Corrosion**: It refers to a local attack among the grain boundaries and granular bodies of a metal’s ship while the rest area of the grain remains unaffected.

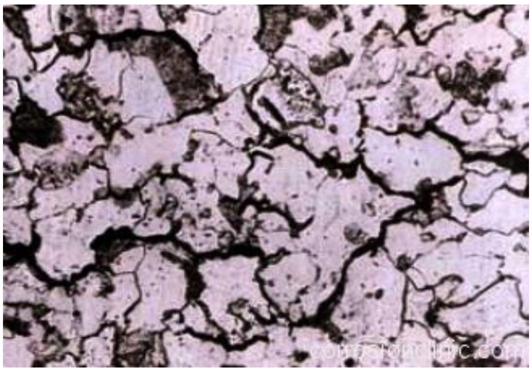


Figure 3.3: Type of Inter-granular corrosion

Furthermore, it must be remarked the fact that corrosion can be distinguished with regard to the size and view of the surface of ship's component after the corrosion. As a consequence, forms of corrosion are **general corrosion** (appeared in large areas and exposes a big surface of steel to the corrosion cycle), **local corrosion** (in excessively stressed structural pieces where water is collected or flowed), **pitting corrosion** (localized corrosion that creates holes in the hull and usually penetrate it) and **weld metal corrosion** or **grooving** (an electrochemical action betwixt the weld material and the basic metal which has as effect pitting or grooving corrosion).

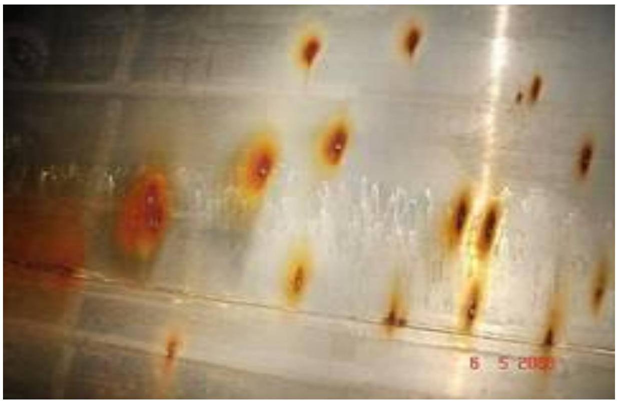


Figure 3.4: Form of pitting corrosion

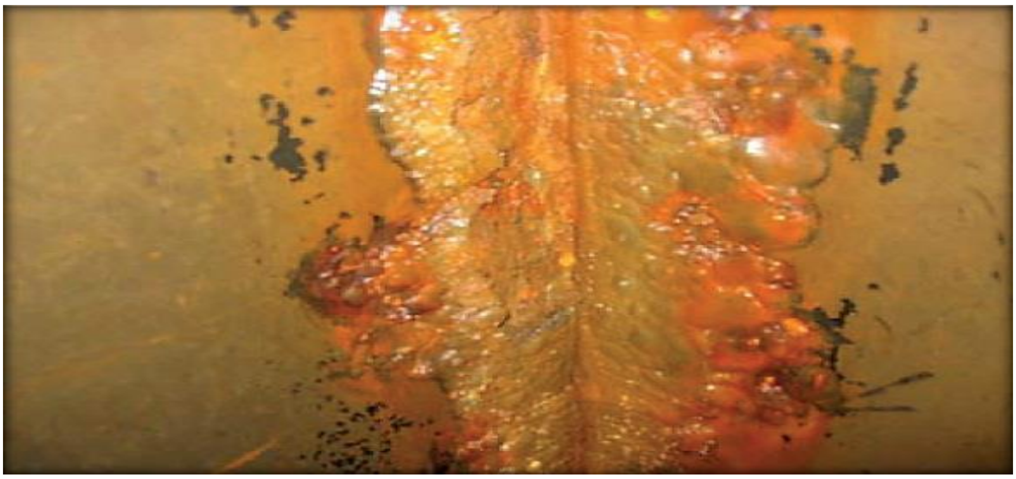


Figure 3.5: Grooving Corrosion in ship's hull

As it can be derived by the aforementioned, there are a lot of types of corrosion which can be located to various spots of a ship. As a result, corrosion can prevent the safe operation of a ship and burden it with heavy loading stresses with a simultaneous deterioration of ship's structure. If corrosion deficiencies would not be repaired in a brief time period, then damage to property may become extremely high and lead to negative consequences for the asset of the shipping company.

Eventually, it is known that corrosion failures can be predicted and measures for their prevention should be taken by every shipping company. Ship owners should have the construction of their ships with the appropriate materials as a priority and demand by shipyards to comply with their commitments to use the proper materials (DNV, 2000). Although that profit and costs are always the most important concerns of a ship owner, sometimes they are not taken into consideration the long term costs that may emerged by an incorrect material or a non-occurrence of a small repair. So, it is necessary during the life of a ship to become inspections in certain periods so as hazards for big extents of damage to be eliminated and safety being reassured.

3.3.2 Fatigue

The phenomenon of fatigue has been observed in ships' structures since the ancient years because of the action of seawater waves and the existence of spots in ships that receive high stress. It is derived by fluctuating stress in the structure of a ship and by the increasing of microscopic cracks to significant cracks after a certain number of cycles.

For the prediction of the speed that a crack grows, a variety of models have developed. The most known fatigue crack growth model used in material science is Paris-Erdogan Law (Papazoglou, 1995). Its equation is:

$\frac{da}{dN} = C \cdot \Delta K^m$, *where* a*=crack length*

N*=number of the load cycles*

ΔK*=the range of the stress intensity factor*

Fatigue failures are usually located in spots of high stress concentration such as baseplate and weldments. Cracks are potentially the most serious failures as they can rapidly develop in size if they are not checked and faced due to the fact that structure becomes more prone to the progressive damage of the repeated cyclic loadings.

Two types of fatigue failure can be distinguished:

- Low cycle fatigue that is happened for low number of cycles, less than $5x10^3$, in the range of plastic deformation.

- High cycle fatigue for high number of cycles for elastically deformed components.

Furthermore, it is known that ship's structural geometry and general configuration could lead to failures that they would possibly derive local stress. Also, in welded points, like joints, it is possible to be produced local increase stresses when the strength of the weld is reduced with regards to that which a base metal has. Moreover, the growth of cracks depends on material defects and the quality of ship's materials as the fatigue life is reduced. Another factor that minimizes fatigue life is the corrosive environment too (Dominique Beghin, 2006).

It is an undisputed fact that nowadays there is a tendency larger ships to be built and materials with better performance to be searched by experts. As a consequence, total strength of a vessel increases but weld areas remain to have a lesser fatigue so the difference of the two values in relation to the endurance differs and failures may arise. For this reason, it is necessary design practices to be improved so as imperfections and local compressive stresses to be introduced and an improvement to the fatigue life to be achieved.

It is obvious that fatigue can cause a lot of failures that it is difficult to be located and faced in an early stage so as cracks and fractures to be deterred. So, it is highly recommended measures to be taken and inspections being held in regular periods. It is found that there must be a monthly check of engine loads and measurements for the cylinder peak pressures. Every year tie bolt tensions and the tension of pump's main bearing jack bolt must be inspected so as pumps and pipes failures to be minimized and possibility for a leakage to be eliminated. The last but not least points that must be supervised are ships' girders which receive high stresses even though that they have the feasibility to resist in deformations and fatigue failures. More attention must be given in main bearings of each girder because are the most hazardous points with respect to their structural failure (IACS, 1999).

Finally, it has to be mentioned that fatigue failures can cost to the property a lot of money if they are not faced quickly. However, it is not only the cost of repairs that may burden ship owners, but consequences and compensations that may be emerged by a leakage of oil or by a leak of a pump with water that will result loss of watertight integrity, must be taken into consideration too. There are observed plenty of accidents that an oil leakage or a LOWI are derived by a crack and significant damages in the equipment of ship occurred. So, it is essential for maritime to become various surveys which will examine all failures that owns to fatigue and outcomes for the costs and the factors that contribute to these kind of incidents to be analysed.

3.4 Approach and Methodology

As ships' operations are characterized by high rates of incidents and dangers, efforts for identifying such dangers and measures for the reduction of existent risks were held by experts. In addition, the involvement of human lives and the presence of a potential pollution which could be derived by marine casualties highlighted the significance for the conduct of a methodological approach which could have dealt with maritime safety.

So, Formal Safety Assessment (FSA) has been developed by the International Maritime Organisation (IMO) owing to an initiative in 1993 of UK Marine and Coastguard Agency. Afterwards, IMO having taken into account the specific proposal established a five steps risk based approach in 1997 which was complied with its regulations. The first FSA study was conducted for bulk carriers.

FSA is a rational and systematic methodology aimed to facilitate the processes of safety management, assess the risks that emerged due to shipping operation and estimate costs and benefits of IMO's recommendations for the reduction of such risk.

Therefore, five steps for the occurrence of each FSA study were established and there are obvious in Figure 3.6.

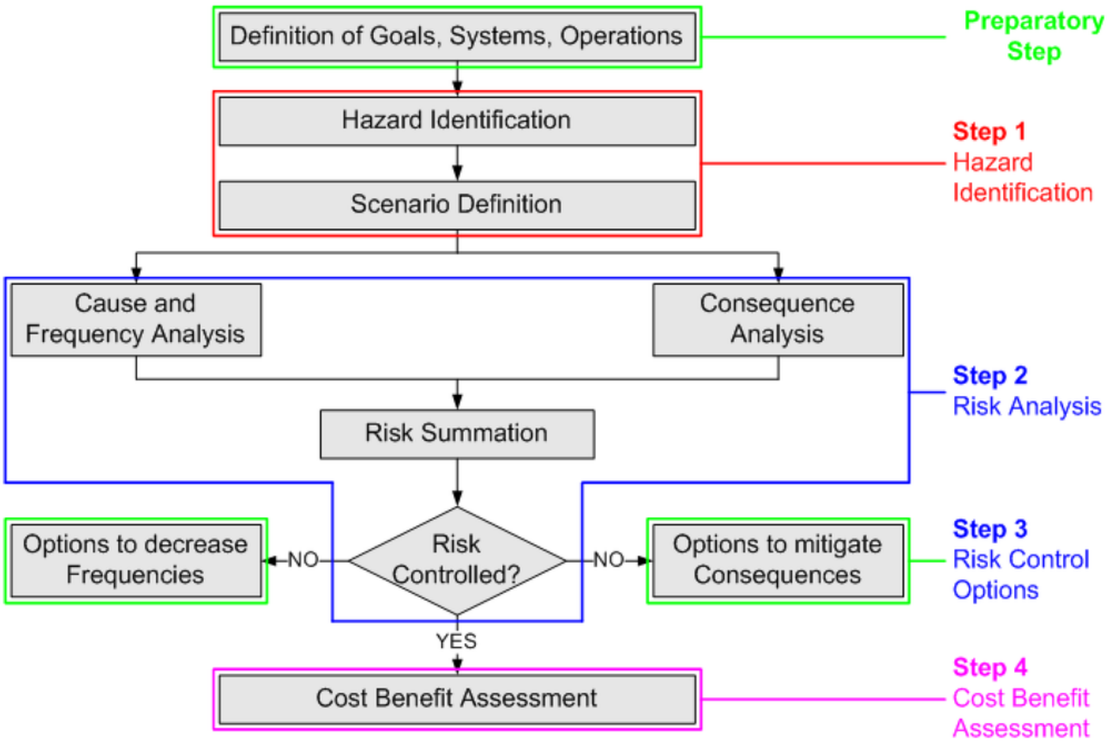


Figure 3.6: Portrayal of FSA's steps

To the beginning of each study, as it can be derived by Figure 3.1, a preparatory step must be implemented so as the decision makers of the problem to reach in its definition (goals, systems and operations). It must be noticed that the problem that is going to be assessed must comply with the regulations of IMO.

Subsequently, the Identification of Hazards has to be taken place. This is the most important step of shipping safety analysis as hazards and their scenarios must become obvious. For current part of each research, experts should acquire knowledge by previous studies or investigate casualty databases with respect to the factors that may lead to an incident so as to find all the issues that could possibly hinder the safety on a ship. Nature and extent of dangers depends on ship type, its size, its operational area etc.

The second step is Risk analysis and is related to the evaluation of the predefined risk factors and their consequences, which are usually considered the fatalities, pollution and economic losses. Their values and their probabilities to occur are estimated for the most hazardous scenarios of the predefined factors that identified in Hazard Identification step. It must be mentioned that it is followed the Probabilistic Risk Assessment (PRA) so as such risks to be estimated. The most common tools for PRA in an FSA study are Event Trees and Fault Trees.

Having comprehended the highest risks of the problem with the aid of Risk Analysis, experts distinguish potential measures for the reduction of the risk or the avoidance of the hazards. Then, they keep those that can be implemented and the Step 2 is followed again. These measures are called Risk Control Options and constitute the third step of an FSA study.

Another aspect of FSA is Step 4, which is consisted of Cost Benefit Assessment (CBA). Owing to the fact that cost is a concerned issue in every sector, the costs and benefits of implemented RCO are estimated with the aim of becoming obvious if the cost to evade a risk is lesser than the potential extent of damage that specific risk could be caused.

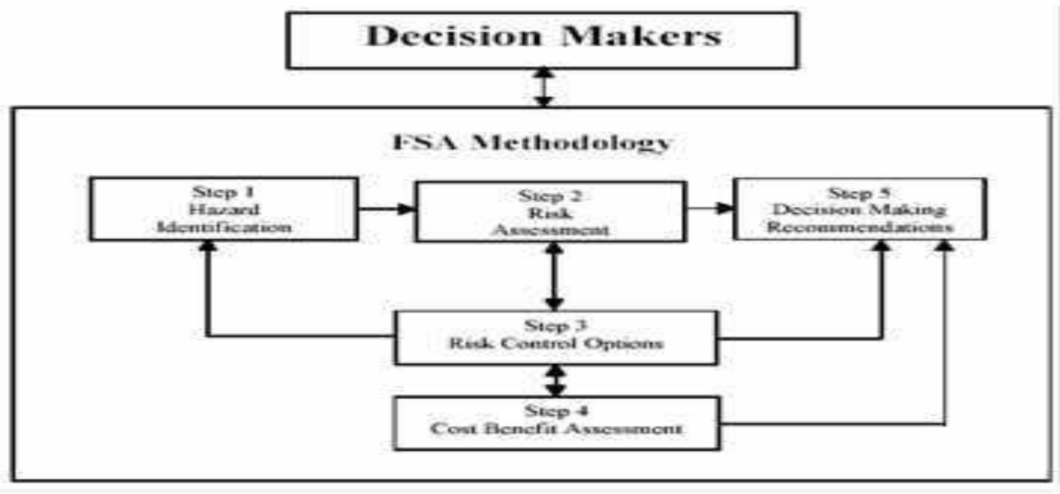


Figure 3.7: Portrait of FSA Methodology

The last, but not the least, step of the specific methodology is the Reccomendations for decision making as it can be noticed by the Figure 3.7. In that stage, it is ensured that solutions that will me given will be the most efective ones with regard to the cost and the reduction of the risk and it usually occurs via the comparison of all RCO's and the consequences of them.

Current thesis was based on the second step of the FSA, which is Risk Analysis, as establishing risk rates for the consequences that can be derived by NASF for RoPax Ships found to be extremely challenging due to the fact that specific isue have not conerned maritime community before. The only approach of this issue had been conducted at 2002 by Japan when structural failures on bulk carriers had been studied and all steps of the FSA were held.

It must be remarked that for almost all ships' types, FSA had already been carried out but without focusing exclusively on Non Accidental Structural Failures consequences.

Risk analysis as it has already been mentioned, can be conducted either with Fault Trees or Event Trees. By personal critical though tforthe characteristics that each of these two modelling techniques have, Event Trees were selected to be developped. That happened because the aim of current research was to acquire knowledge for the consequences of the investigating incidents and quantificate them (Event Tree) and not to pursuit a qualitive approach for the causes of specific casualties (Fault Tree).

Event Tree Analysis

Event tree analysis (ETA) has as basic characteristics the identification and the evaluation of event sequences for a potential incident scenario which follows the occurrence of an initiating event. As incident scenario is defined the series of event which finally engender an accident.

Event tree is one of the most known methods for the development of a probabilistic risk assessment (PRA). PRA is a logical analysis method that is usually used so as to identify and evaluate risks, which are related to a complex technological system, based on accident scenarios and factors that will lead to a hazard situation, scenarios frequencies for the comprehension of the extent of possibility to go something wrong and scenarios consequences that are associated with the outcomes and the damages that will derive by the whole system.

It is quite essential for this kind of analysis to be followed specific steps during the developing process so as this method to be constructive. These steps are mentioned below:

- Initially, there must be a clear definition of system boundaries and subsystems as a plan for the process must be made before the building of the event tree.
- In the sequel, hazards and accident scenarios that are emerged by the system design are to be identified.

- Moreover, after a critical thought with respect to hazard analysis the initiating event must be determined. The decision for the definition of the initiating event is one of the most important issues in all process because it is responsible for the consequences that system will be showed and the intermediate events that will exist to the event tree.
- As a consequence of the determination of the initiating event, intermediate events or different components are derived and the most perceivable and interesting ones in relation to the starting event must be selected. This is a very difficult step as their coherence and their sequence will not allow to the tree to have a big amount of branches and becomes too complicated and sometimes with illogical accident sequences.
- It must be remarked that except for the definition of the events, potential results of each event must be considered too. Usually, two binary states are assumed for the results of simplified trees and either are yes and no, or success and fail. However, it is widely known that trees which deal with advanced issues are consisted of more than two potential cases and they are not of the nature of a negative or a positive answer.
- After all above steps, it is feasible the event tree to be constructed and probabilities for each branch of event to be completed so as to calculate the final possibility of each route of events and outcomes or consequence to be evaluated.

It has to be mentioned that for each component, the sum of the probabilities must be equal to 1. If we assume that potential branches of each event are shown as B_N with N represents the number of component branches and i shows the series of event, then it can be derived that:

$$\mathbf{P_i\,(B_1) + P_i\,(B_2) = 1,} \qquad \textbf{\textit{if N=2}}$$

$$\mathbf{P_i\,(B_1) + P_i\,(B_2) + \ldots + P_i\,(B_N) = 1,} \qquad \textbf{\textit{if N>2}}$$

Also, the final possibility of the outcome of each scenario, the result of a route of branches, is estimated by multiplying the possibilities of each concerned branch in specific route. For example, for the first outcome of a developed event tree, outcome A, it is obvious that probability is:

$$\mathbf{P\,(A) = P_1\,(B_1) \times P_2\,(B_1) \times \ldots \times P_I\,(B_1),} \qquad \textbf{\textit{i=1, 2, ..., I}}$$

An example of event tree is presented below and aforementioned can be easily comprehended:

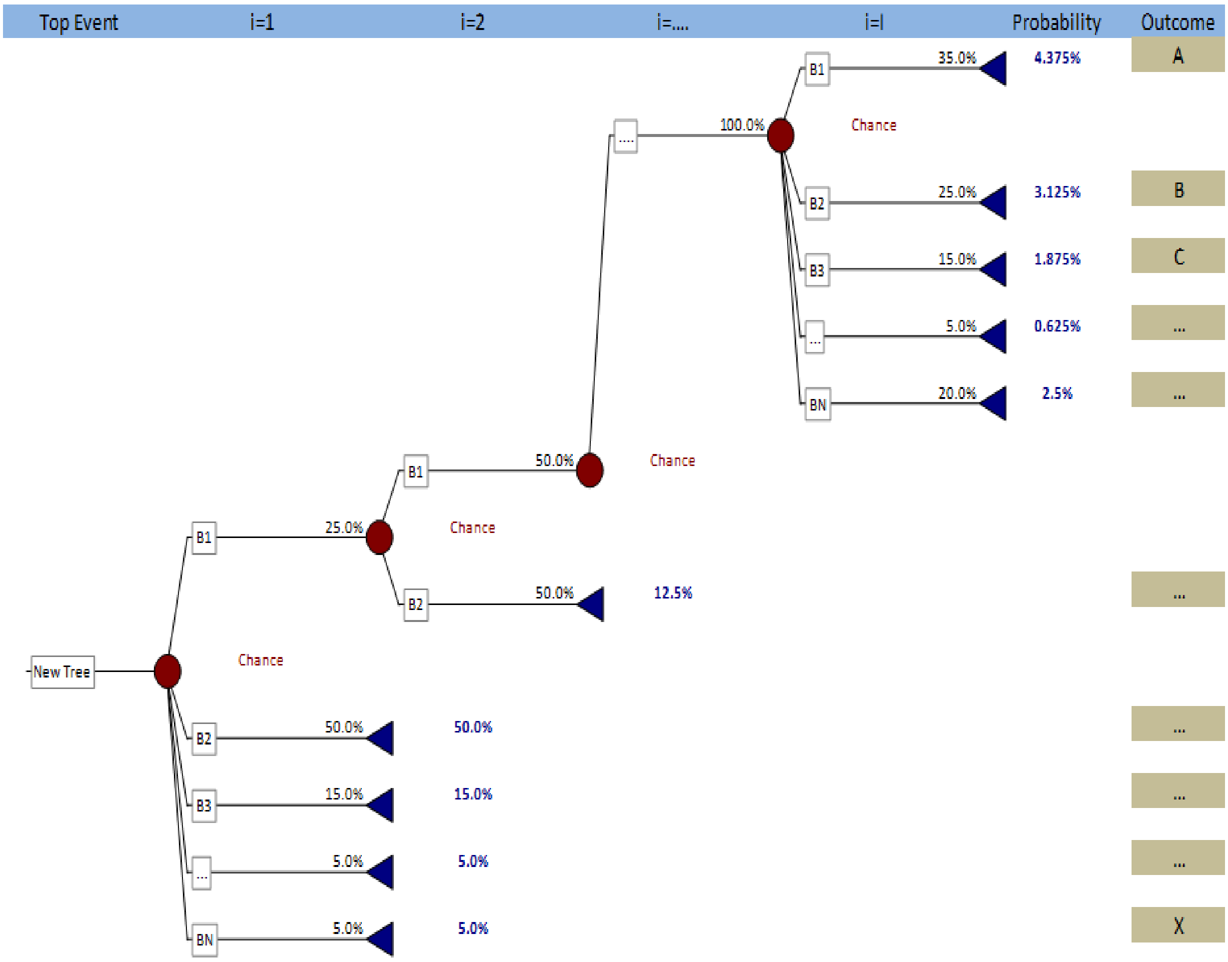


Figure 3.8: Sample of an Event Tree

Although ETA has a wide variety of advantages as risk can be assessed and consequences can be evaluated, its approach presents two serious drawbacks. The latter is that in each event tree only one primary event must be existed and its consequences are to be evaluated so for the evaluation of other initiating events other event trees should be developed. The former is that this method requires some training and practical experience for its appliance because of the difficulties that are presented during the selection of the events which are going to be included in the analysis and the proper choice of values that are used for the evaluation of the consequences of each outcome.

3.5 Steps of Consequence Analysis

The consequence analysis was conducted through the following process:

1. Analyse historical data of the of RoPax vessels from SEAWEB casualty database.

2. Risk analysis and develop Event trees based on the casualty data.
3. Quantify the consequences of corrosion and fatigue failures for RoPax ships.
4. Compare the outcomes of the Risk analysis with theoretical values according to the whole fleet.

3.5.1 Historical Data Investigation

Current research had as a starting point the identification of the significant accidents that could affect ship's operation and cause some serious and negative impacts on the environment. Historical data of RoPax ships are exploited so as species of marine casualties to be recognized and their distribution in RoPax fleet become known to everyone.

There are 6 main categories of marine accidents that were distinguished by database and are presented below:

- Collision
- Contact
- Fire/ Explosion
- Foundering
- Hull/Machinery Damage
- Stranded/ Wrecked

Some indicative percentages and figures are given with the aim of presenting a general tendency of RoPax fleet to accidents. But an elaborated statistical analysis was followed with regards to Non Accidental Structural Failures for the deepest comprehension of these types of incidents that have not yet been investigated for the selected type of ship (RoPax).

NASF events due to structural degradation consist of scenarios where the hull present cracks, fractures, dents and corrosion, all of whom affect the vessel's seaworthiness or efficiency. It has to be remarked, that at present study was taken in consideration cracks and corrosion which occurred in tanks and pipes too.

After a critical review it decided to examine in detail casualties that were registered to the description of database as Foundered, Stranded/Wrecked and Hull/Machinery Damage. Their meaning is presented below:

- **Foundered:** This situation indicates that a ship sank because of a leak or was overcome by wind and waves. It is always derived by failure of ship's cross section and loss of watertight integrity.
- **Stranded/Wrecked:** Accidents of this category are characterized by an unintentional contact of ship with sea's bottom or a stable submerged object as a wreck or a reef. It is obvious that a ship in this status cannot refloat without

assistance. It must be mentioned that in specific analysis the initial point of the accident was a crack or the appearance of corrosion and the consequence was the stranding or the wreck.

- **Hull/Machinery Damage:** Although strength of ships and quality of the materials that are used in ship's hull is a topic of key interest to naval architects and shipbuilders, hull damage usually occurs during the life of a ship. In present thesis as Hull/Machinery Damage was assumed the structural failure of ships' hull and pipes due to the fatigue and the corrosion that occurred in each component. It must be noticed that machinery damage corresponds to pipe failure and hull damage refers to hull's failure.

The next step of the analysis was to identify various factors and differentiate the consequences based on the details of the elaborated casualty reports. These factors are taken into consideration with regard to the affection that each of presented terms may have, on the comprehension of a casualty. These factors are:

1. **Weather:** It shows the weather conditions that prevailed at the time of the accident. Two categories are distinguished and they are labeled as "Heavy" and "Light". "Heavy" weather indicates to winds, storms and rough sea, while "Light" weather label represents calm sea, sunshine and generally good weather conditions.
2. **Operational Situation:** It refers to whether the ship was "On voyage" or "At port" when the accident occurred. This term is significant because the immediate response of the authorities and generally the instant assistance in a case of casualty depends in a high grade on the location of the ship.
3. **Loading condition:** A factor that contributes a lot in the occurrence of a structural failure is the loading condition that ship was when the incident happened. There are two records which are enumerated, the first one is the note "Loaded" that refers to a ship which contains full of cargo and the second one, "Empty" note that lead to the conclusion that ship is in Ballast condition or it sails without cargo.
4. **Degree of Severity:** It is expressed as "Minor", "Significant", "Scrap", "Refloat" and "Total Loss" by the experts of database. "Significant" accidents remarked those which had serious injuries, fatalities and hull damage that led to an extended detriment with negative consequences for the property and ship's operation. On the other hand, the label "Scrap" intimated that ship was taken for scrapping because it was uneconomic for the company owner to repair it. Moreover, "Refloat" implied that when a ship had suffered from foundering, salvage companies managed to transfer it to the drydock so as to be reconstructed. While "Total Loss" meant that ship was sunk independently the fatalities and the injuries that may be occurred.
5. **Loss of Watertight Integrity (LOWI)**: Label "Yes" implies the presence of water ingress during the accident and label "No" shows that ship did not take water at the accident.
6. **Time:** The last point that investigated at this initial general analysis was the time that casualty took place. Time expressed with "Day" or "Night" notifications so as to highlight the time of the appearance of the failure. Of

course, it has to be noticed that the precise time of the inception of failure cannot safely be ascertained.

7. **Starting point:** As starting point is recorded in current analysis the area where the failure occurred. Three areas can be distinguished and can contribute to the study. Investigation revealed that an incident can be observed in the aft area of the ships (aft peak tanks and engine room area), cargo space and forepeak area.
8. **Location:** This includes bottom shell, side shell, inner bottom, floor, exterior deck and interior deck. It must be noticed that term location implies the location of the initial point of failure.
9. **Progression of Damage:** It contains information about the upcoming events that derived from the initial failures. "Failure of Cross Section" which means that ship damaged and foundered, "Leakage" which could be observed when a quantity of oil or water sprang from a tank or pipe due to NASF and "No" which refers to the non-subsequent failure can be distinguished and create three categories for this factor.

All aforementioned factors are considered as significant for the occurrence and the sequel of an accident. Even though some of these factors would contribute to the creation of the perception regarding to NASF casualties, it was necessary to develop a statistical analysis for specific classes of GT with respect only to the weather, operational area, loading condition, time, LOWI and degree of severity. It was considered as necessary so as to exclude some general and initial outcomes for each class that was specified and is not going to be developed in the risk analysis.

3.5.2 Risk Analysis and development of the Event Trees

Although statistical analysis of database can lead to some conclusions, it is not proactive and cannot be used for new designs as existing or dead ships are taken into consideration (Kontovas and Psaraftis, 2009). So it is necessary to develop a probabilistic modelling of the failures with the assistance of scenarios that would contribute to the occurrence of a Risk Assessment. This process is going to be implemented with the method of Event Tree Analysis.

The event tree defines graphically all possible consequence scenarios which are evolving from an identified risk named top event. The top event represents an accident, a failure or an unintended event. These consequence scenarios can be classified into three types, initial events which are the primary consequences of top event, dangerous effects which are the dangerous consequences of second events and major events of each dangerous effect which are ultimately the final consequences (Badreddine and Amor 2010). This methodology is usually applied when the consequence spectrum from the determining hazard (top event) is threatening lives, asset and environment and all the possible scenarios is of major importance are analysed.

They are a proven concept in the maritime industry as this methodology was used from IMO for the elaboration of the FSAs for different ship types (IMO 2005, 2007a, 2007b, IMO 2008b, IMO 2008c and IMO 2010b). Based on the elaborated statistical analysis of the casualty database numerous Event Tree diagrams were developed aiming to the identification and quantification of the consequences emerged after these accidents.

Taking the background information and the initial analysis of the accident reports into account, accidents under concern (NASF incidents) are segmented into the following 3 major accident scenario groups:

1. Flooding due to structural failure
   1.1. Water ingress in F.P. area due to structural failure
   1.2. Water ingress in cargo holds due to structural failure
   1.3. Water ingress in area due to structural failure
   1.4. water ingress due to a bottom shell failure
   1.5. water ingress due to side shell failure
   1.6. water ingress due to inner bottom failure
   1.7. water ingress due to floor failure
   1.8. water ingress due to exterior deck failure
   1.9. water ingress due to interior deck failure
2. Structural failure without water ingress
   2.1. Structural failure to cargo holds without water ingress to cargo holds
   2.2. Structural failure to F.P. area without water ingress to cargo holds
   2.3. Structural failure F.P. area without water ingress to cargo holds
3. Failure in tanks or pipes due to corrosion or cracks
   3.1. Leakage from a tank or pipe
   3.2. No leakage from a tank or pipe

These accident scenarios formed the basis for the development of the final event trees. It was decided to develop the event trees in relation to 9 factors that were explained above and the expanded tree that was emerged was quite complicated and confusing

It became obvious that specific event tree was consisted of 2000 scenarios, something that would make the investigation extremely complicated and it would be impossible to reach in safe conclusions as the sample of NASF incidents was contained only 200 circumstances.

After a critical review, it was determined to simplify the event tree and keep only 5 events that were compatible with the factors that were mentioned above. Simplified Event Tree has as events the initial Starting Point, the Location, the Progression of damage, LOWI and the Degree of Severity. Simplified tree is presented in Appendix A (Figure A.1) and contains 112 scenarios.

3.5.3 Quantification of the consequences

Risk Assessment is going to be completed with the quantification of the consequences and some indicative values for the cost of the damage to property that were estimated with respect to worldwide market. Guidelines for presented quantification were acquired by International Association of Classification Societies (IACS), basing on Formal Safety Assessment and developing this type of Assessment by other ways.

Cost of Damage to Property

In this chapter, the determination of the expenses of ship owners is explained as incidents are expected to cause significant issues to ship companies.

The cost factors that are taken into consideration are presented below:

- **Value of Ship (in case of total loss or scarp):**
    1. The veritable value of a ship that is lost due to an accident is determined by a formula which was given by DNV- GL. Its equation is $Cost=76{,}976*GT^{0.7663}$. So, for every loss of the ship, its Gross Tonnage was found by the database and its cost was estimated.
    2. In addition, when the ship is foundered there was observed in some situations that Refloat of ship occurred and the costs of this kind of operation with regard to FSA were estimated in a percentage of 25% of the cost which would be considered in case of Total Loss.
    3. Finally, in some occasions it was observed the scrapping where damage of the ship was extremely serious and owner decided to give the ship for scrapping. This value was based on the estimation of the average LS for the two concerned categories of GT. For ships with 4,000GT and below, it was found that the average Lightweight (LS) of the investigated fleet was about 700tonnes and the price of owner’s compensation was about 200 euros/LS. Moreover, for the other category average LS were found about 4,000tonnes.
- **Costs for loss of Cargo (in case of Total Loss):** In a variety of occasions that an accident occurs, the cargo of ship may be damaged. As cargo for RoPax vessels are considered cars or general some species of vehicles and passengers. It is obvious that a human life cannot be estimated as it is priceless. Cars, trains and trucks can be estimated and in the case of an

accident, owners will be compensated, but the compensations burden insurance companies without affecting ship owners.

- **Repair Costs:** Repair costs consist of three terms of cost. The first one is the Cost for Repairs that contains the costs of the dry docking (labour costs). Also, in this type are deducted costs of the material that are used during the repairs (steel, equipment). The second one is characterized as Loss of Income and refers to the amount of money that a company would earn if the ship was in operation. The last category of repair costs concerns Costs for Crew. It is known that some members of ship's crew are hired during the repairs. Due to the inadequate data, repair costs will not be taken into consideration in the determination of the potential cost.

Environmental Impact

After a detailed investigation, it was feasible to estimate the pollution rates. The process for this analysis began with the recording of the situations that pollution was observed by database and the amounts of oil that spilled wherever it was given. Only in 3 cases, specific values for the size of the oil spill were given. As a result, tank capacity of each ship was obtained and a value of 30% of specific capacity was assumed so as to take rates for oil spills which derived by the total loss of the ship and a value of 2% for the cases where a small oil spill occurred.

3.5.4 Comparison of the consequences

The last issue that this thesis deals with is the cumulative risks assessment for the pollution and the damage to property basing on the whole fleet of the database and without taking only into consideration the existent accident reports.

The aforementioned percentages with regards to tank capacities for each Degree of Severity were used while a new formula which was proposed by DNV-GL for the estimation of ships' fuel capacities was taken into account. Its equation was $TankCapacity=0.1665*(GT*Speed)^{0.6939}$. So, having been aware of the values of the Gross Tonnage and Speed of each ship of the whole fleet, theoretical values of the pollution were assessed with respect to the predefined cases. For the calculation of the costs, a similar process to the Risk Analysis was followed but with the only difference that data for all fleet was considered. Finally, it must be remarked the fact that the probabilities for the occurrence of pollution and the damage to property for each degree of Severity in each occasion (e.g. Large class with corrosion) were taken equal to those that were derived by the existent data of NASF.

4. Casualty Data Analysis

4.1 Origin of information

This research was based on IHS Casualty Database which was provided by National Technical University of Athens, and contained casualty historical data for a large time period. In present study, data for various accidents that occurred in the period 1985-2016 for RoPax ships obtained by the database. The reason for the selection of this period was the combination of a contemporary and adequate fleet so as to be ensured that the process will be reliable.

Database contained various elements for RoPax accidents. The current fleet of RoPax in database was analysed from different aspects with respect to global trend and national regulations. For the specific fleet found 3707 casualties, which their figures with regard to Gross Tonnage (GT) are presented in detail below:

GT Ranges	Percentage of Fleet (%)
Up to 1,000	45.43
1,000-4,000	25.17
4,000 and above	29.40
TOTAL	100

Table 4.1 The proportion of fleet classified in 3 categories

Furthermore, Figure 4.1 illustrates the distribution of the age of RoPax ships it is obvious that 34% of the ships which were involved in an accident represent ships less than ten (10) years. As a result, it can be presumed that this study based on contemporary data which can produce useful results for the future of maritime transport.

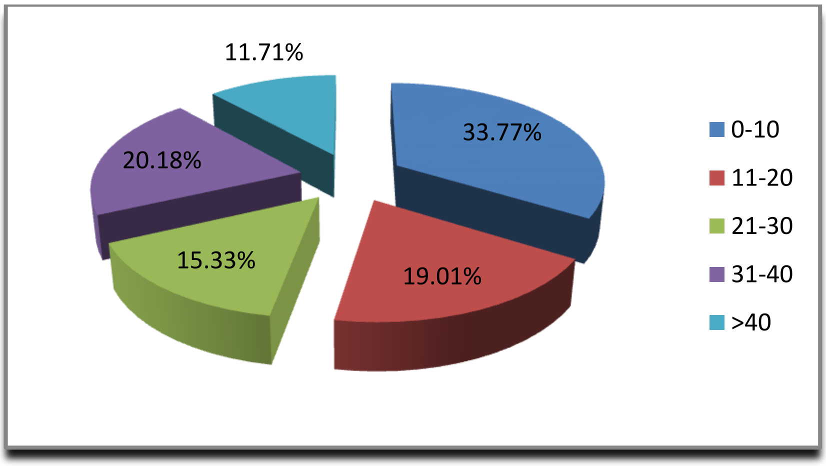


Figure 4.1: Considered fleet's age

Another analysis that was held was the separation of speed in regard to the classes of GRT while RoPax are not characterized by a particular width of speed due to the innovative designs that exist in the world market and the different needs of each operational area. So we can see analytically for the specified categories of RoPax:

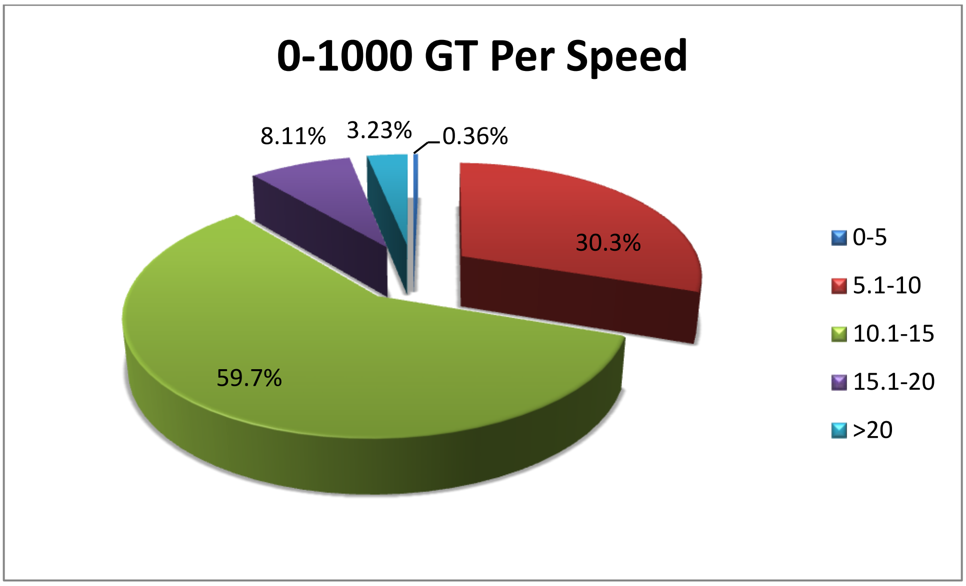


Figure 4.2: Percentage of speed in small category of RoPax

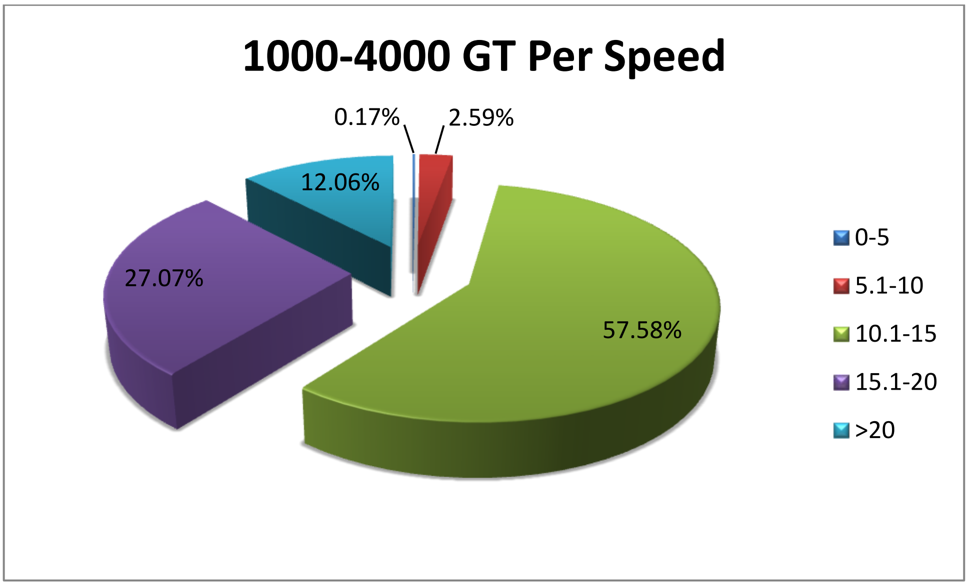


Figure 4.3: Percentage of speed in medium category of RoPax

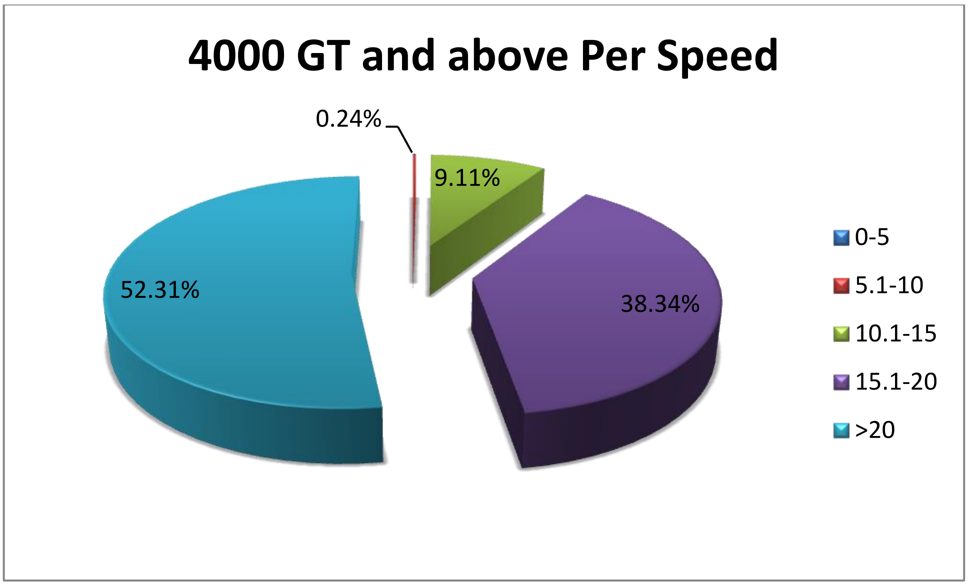


Figure 4.4: Percentage of speed in large category of RoPax

The above diagrams dictate that while GT is increasing, the average speed of each category changes. It can be noticed that in small and medium category, ships' speed is usually between 10.1-15 knots. But the second width of these two classes differs and the findings show that for the small category, speed ranges between 5.1-10 knots and for the medium category betwixt 15.1-20 knots. The third class of RoPax ships is characterized by a great value of speed and it is easily to come across unbiased by the Figure 4.4 that is higher than 20 knots. So, it seems that while GT increases, speed increases too. Something that is logical because of the analogy between GT, ship particulars and the requirements that arising.

The type of incidents that database contained was about 7 categories, except for the category unknown that is consisted of the inadequate data for the casualty type and their amount and percentage presented below:

Accident Category	Number of Casualty	Percentage(%)
Collision	454	12.25
Contact	591	15.94
Foundered	103	2.78
Hull/Mach. Damage	1,087	29.32
Wrecked/Stranded	487	13.14
Fire/Explosion	379	10.22
Unknown	606	16.35
Total	**3,707**	100

Table 4.2: Casualty Statistics and number

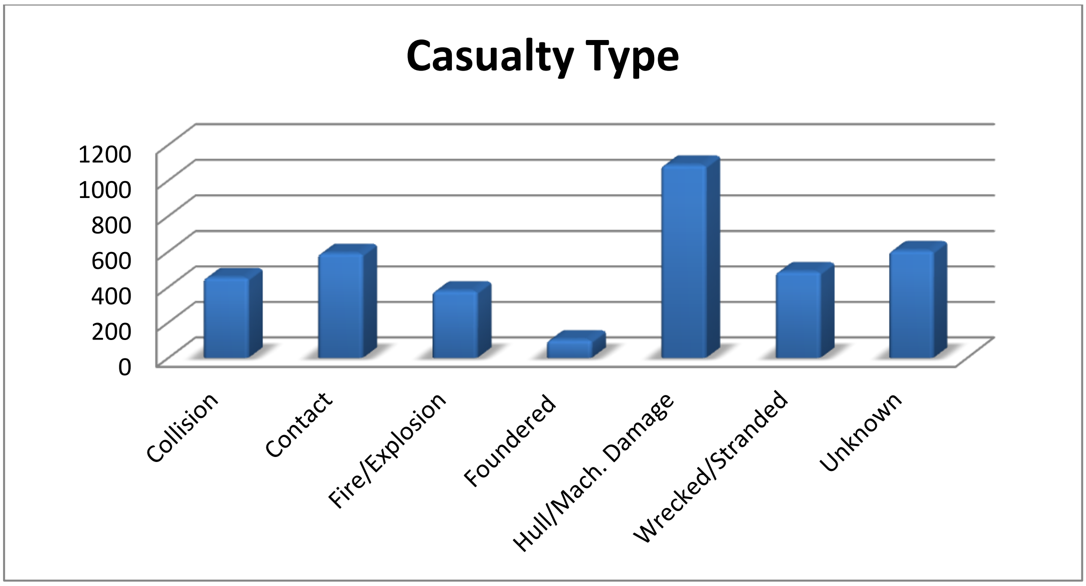


Figure 4.5: Proportion of casualty type in the fleet

Consequently, Hull/Machinery Damage seems to be the most significant category of incidents that occur in RoPax. The following categories are Contact, Wrecked/Stranded and Collision.

5. Statistical Analysis of Non Accidental Structural Failure

Having examined all the casualty reports that were recorded in the concerned database and by taking into consideration that our sample must be consisted of RoPax ships with Capacity≥ 200 GT for reaching safe results (European Commission, 2015), the amount of *200* accidents with NASF was found. As a result, it was feasible to analyse all these accidents by a lot of aspects.

5.1 Generic Analysis of NASF

The statistical data in terms of accident type of NASF and the number of each category are given below:

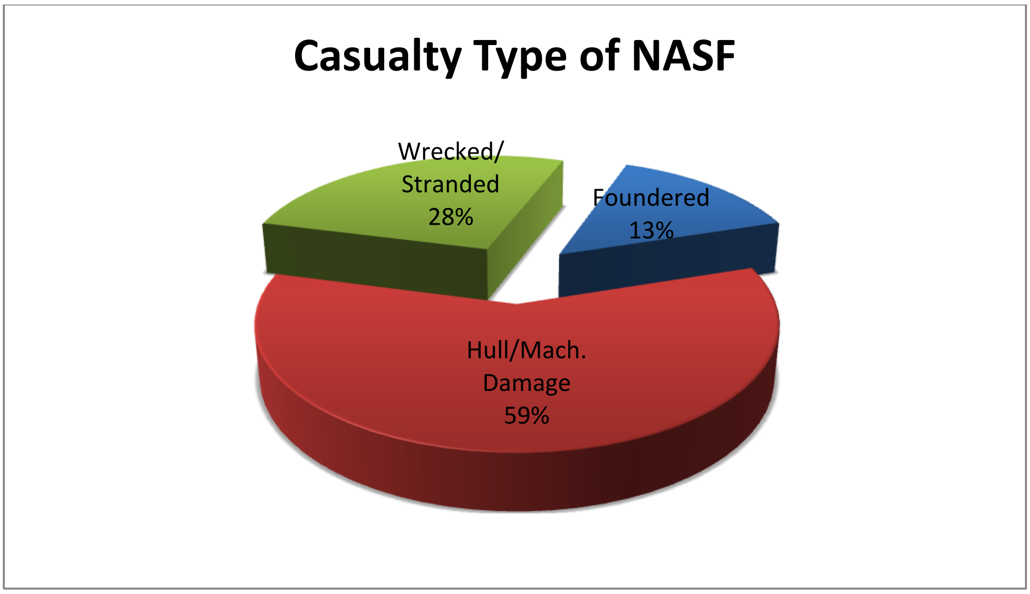


Figure 5.1: Casualty type and percentage for NSAF

Casualty Type	Number of Incidents	Percentage (%)
Foundered	26	13
Hull/Mach. Damage	118	59
Wrecked/Stranded	56	28
Total	200	100

Table 5.1: The amount and percentage of each category

By interpreting Figure 5.1 and Table 5.1, it is obvious that NSAF led to *67 Foundered* and 43 *Wrecked/Stranded* events, something which indicates the significance of the NASF accident.

Total Sample of NASF

All scenarios of NASF (*200* incidents) were analysed with regards to some interesting factors (Figure 5.2). For about *175* incidents (87%) data according to the operational situation were given. Investigation of these reports showed that 61% of the casualties occurred while the ship was "On voyage".

In 66% of concerned reports the weather at the time of the accident was mentioned. Descriptions of database contributed to reach to a result that 76% of the incidents (*100* incidents) took place under heavy weather.

Furthermore, database described ship's loading condition for *179* out of *200* cases of failures. So, it was easily found that 65% of specific incidents occurred when vessels were "Loaded".

Another factor that is shown in above diagram (Figure 5.2) is the time that the failure was appeared. Provided that 84% of the reports referred to information in relation to the time, it can be emerged that 110 out of 168 (65%) casualties occurred during the day.

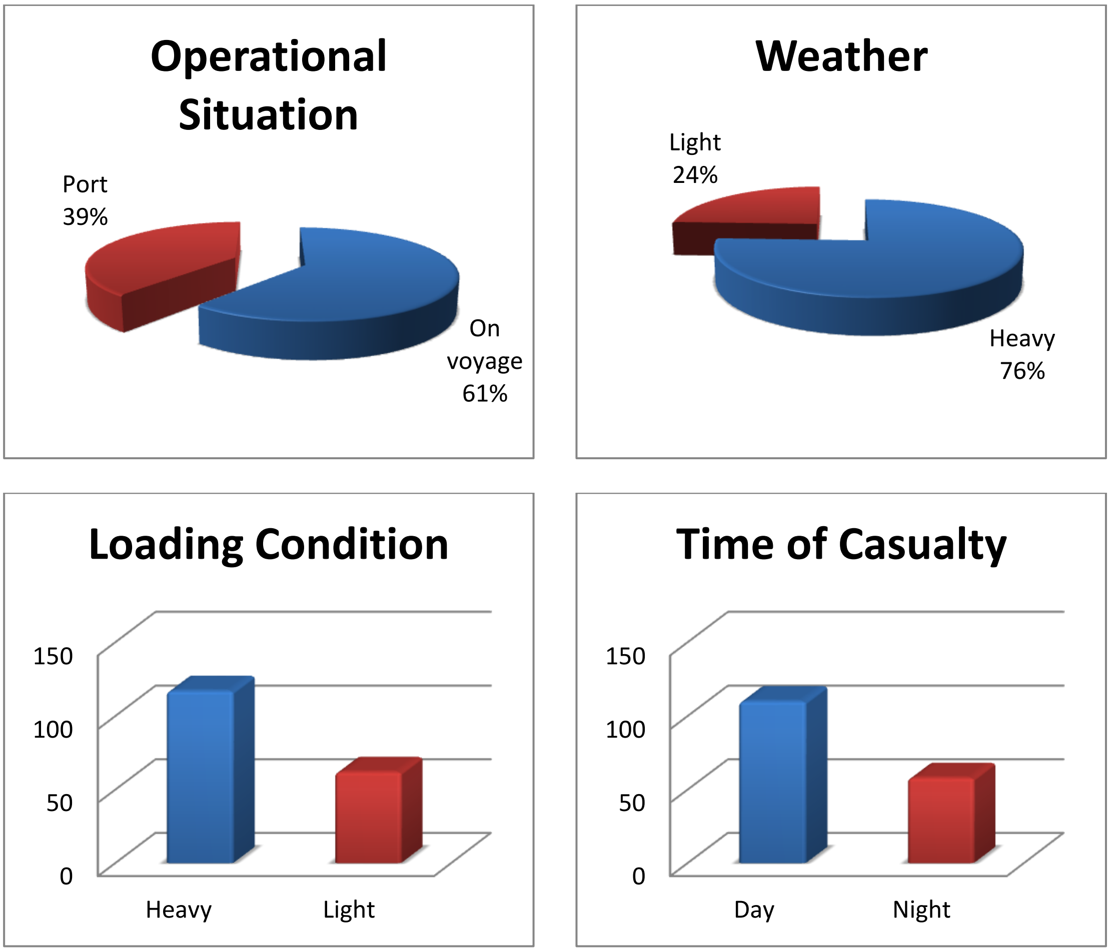
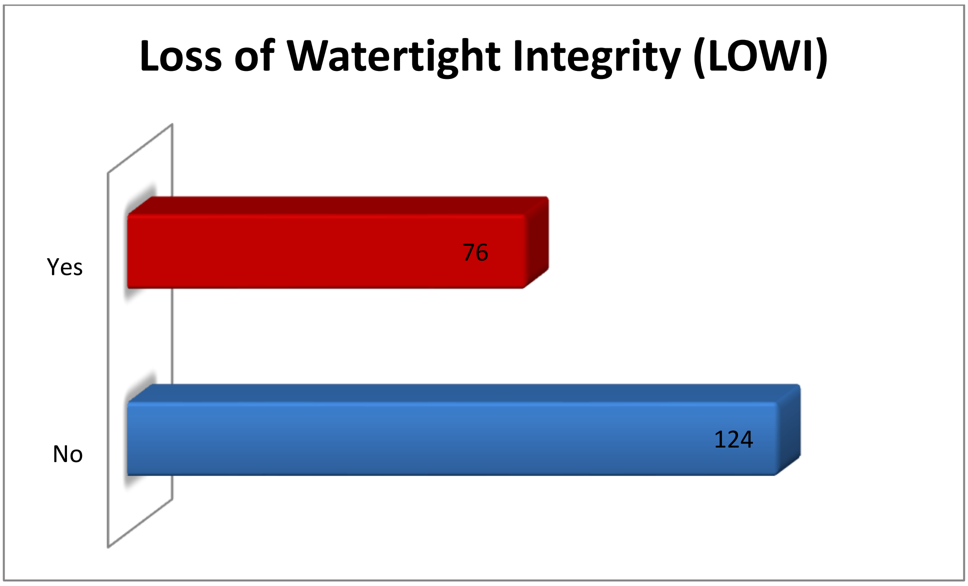


Figure 5.2: Features of operational situation, weather, time and loading condition for NASF casualties

Eventually, the last two factors of the statistical analysis that were taken into consideration referred to Loss of Watertight Integrity (LOWI) and the Degree of Severity of the accidents (Figure 5.3). Information for all incidents with respect to these factors was acquired either by specific database or Internet. It is obvious by

Figure 4.3 that for about 38% of the occasions were observed LOWI. While the highest percentage of the Degree of Severity remarked for the significant incidents.



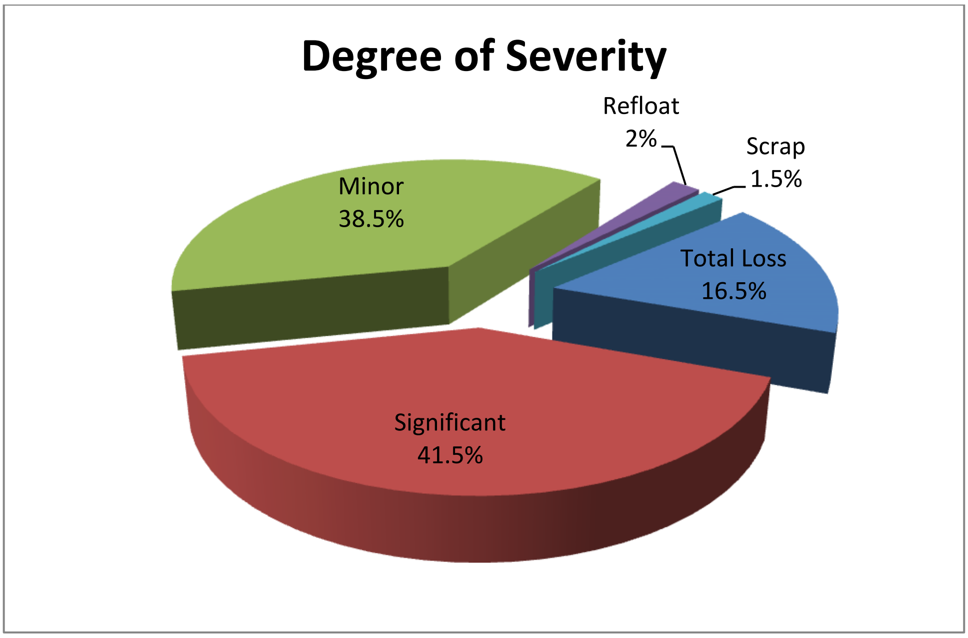


Figure 5.3: Features of LOWI and percentages of Degree of Severity for all NASF casualties

Foundered

Foundered scenarios accounted for 13% of this type of accident (Figure 5.1). In 96.5% of all reports an operational situation was specified. The majority of these accidents observed when ships were on voyage (57%).

The database was also analysed with respect to the loading conditions of the ships, the time of each incident, the weather at the time of each incident, and the severity of each casualty (Figure 5.4). For foundered accidents 100% of the data for the loading condition, the weather, the time and severity were given. As it derives from these figures most of the incidents occurred under heavy weather (78.6%), in loaded condition (60%), leading to total loss (82%) and during the day (57%).

The main cause to consider the loading condition is the impact of cargo and the pollution to the loss of property. The severity of each accident shows in which occasions the loss of ship happened so as to be taken in consideration the loss of property and the expenses of the property for compensations when it was noticed pollution. Also, it becomes perceivable that ship sometimes can be refloated and by the assistance of experts ship can return in operation. The factor of Loss of Watertight Integrity (LOWI) needn't to be considered, as in foundered casualties, it is known that LOWI always exist.

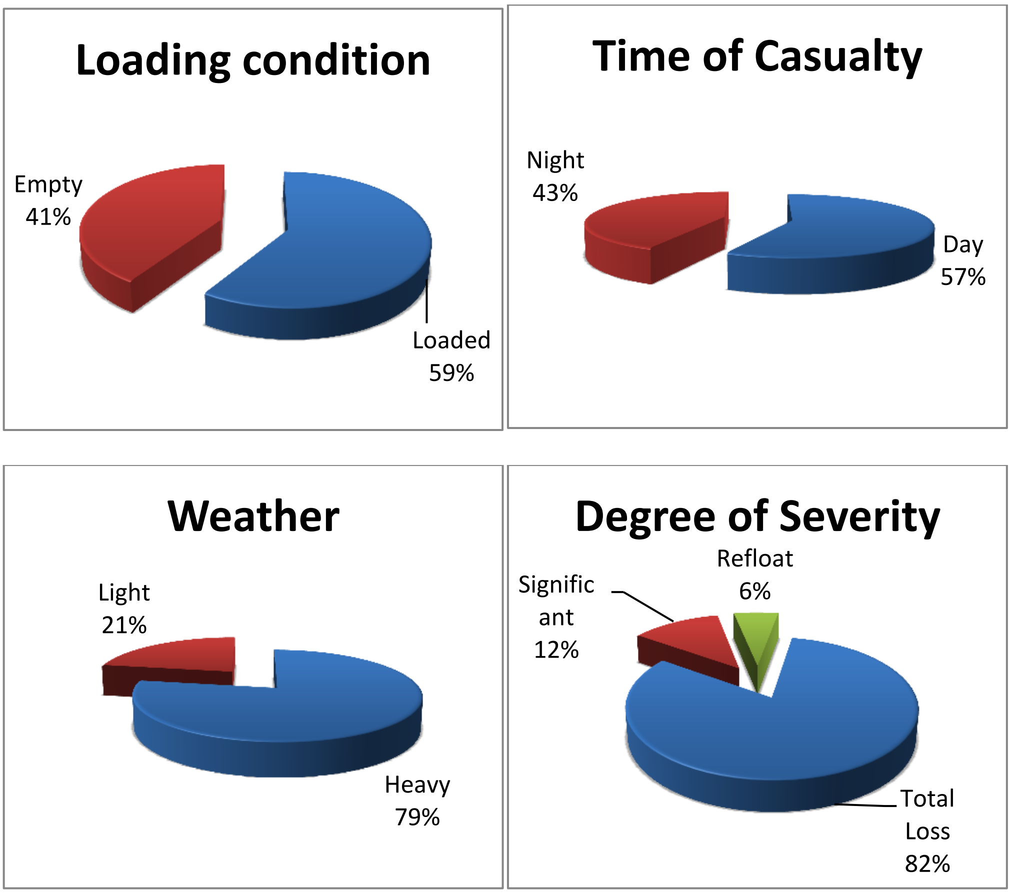


Figure 5.4: Features of the weather, severity, time and loading condition for Foundered casualties

Hull/Mach. Damage

The Hull damage investigation is developed on the basis of *118* casualty reports. Adequate information allowed the portrayal of the characteristics of each incident and the production of conclusions in relation to weather, operational situation, loading condition and time of the occurrence of present casualties (Figure 5.5).

For about 76% of the accidents information was available with respect to the loading conditions and approximately 63% of those types of accidents happened when ships were loaded. The reason of why that happens can be justified because of the higher pressure that hull suffers when ship contains a perceivable amount of cargo and the bending moments that are created because of fatigue that comes from the continuous stress of the hull.

Furthermore, data for the 94% of the sample was given for the operational situation and it derives that 59% of current accidents take place while the ship is on voyage (Figure 5.5). In addition, in *42*out of *86* cases have not been specified the weather but it is feasible to reach the conclusion that 79% of the incidents with the existing data occur in heavy weather.

Needless to say that 74% of the 56 cases of provided information with regard to time remarked that hull damages took place during the day (Figure 5.5).

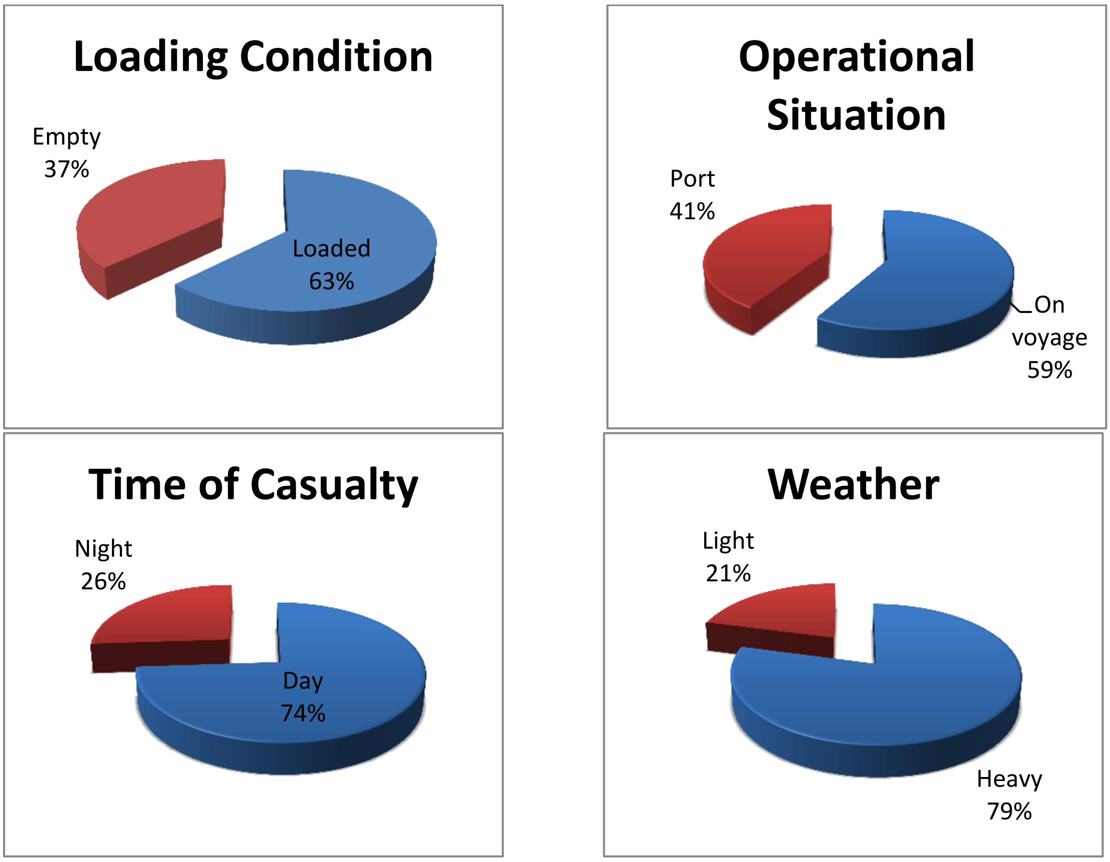
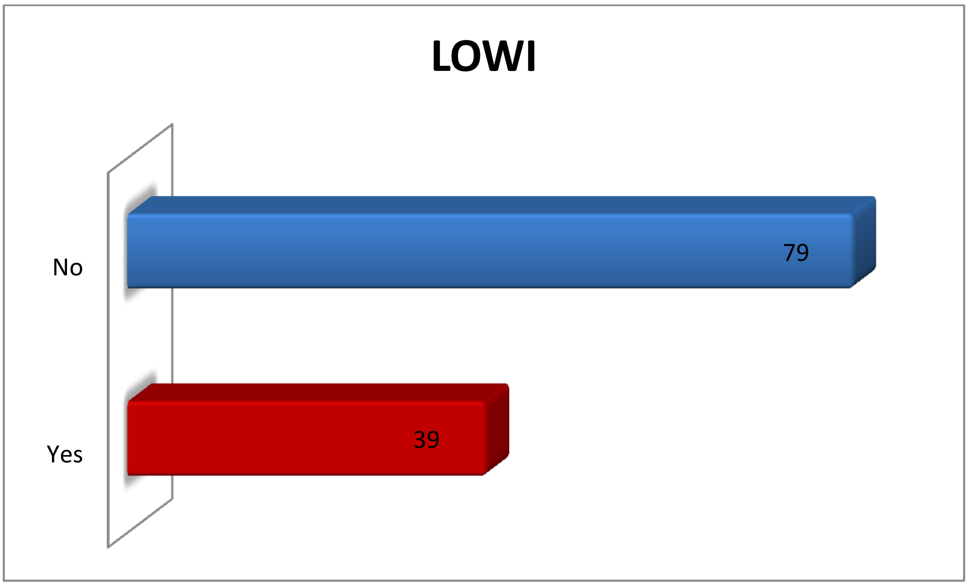


Figure 5.5: Features for loading condition, operational situation, and time of casualty and weather of Hull Damage incidents

Conclusions for the severity and the LOWI of each casualty can be safely resulted as complete information was given for all casualties of this category. The interaction of these two types is shown in Figure 5.6 where it is obvious that in 33% occasions (39 cases) noticed LOWI while total Loss percentage reached only to 1% (2 incidents) of the percentage in severity. As a result, when LOWI occurs in low rates, total loss is not very possible. Of course, it must be remarked that LOWI effect does not mean the loss of the ship. Another important rate is the two (2) refloats that were observed in this type of incidents. Also, it must be highlighted that fifty-one (51) out of 118 were characterized minor by database.



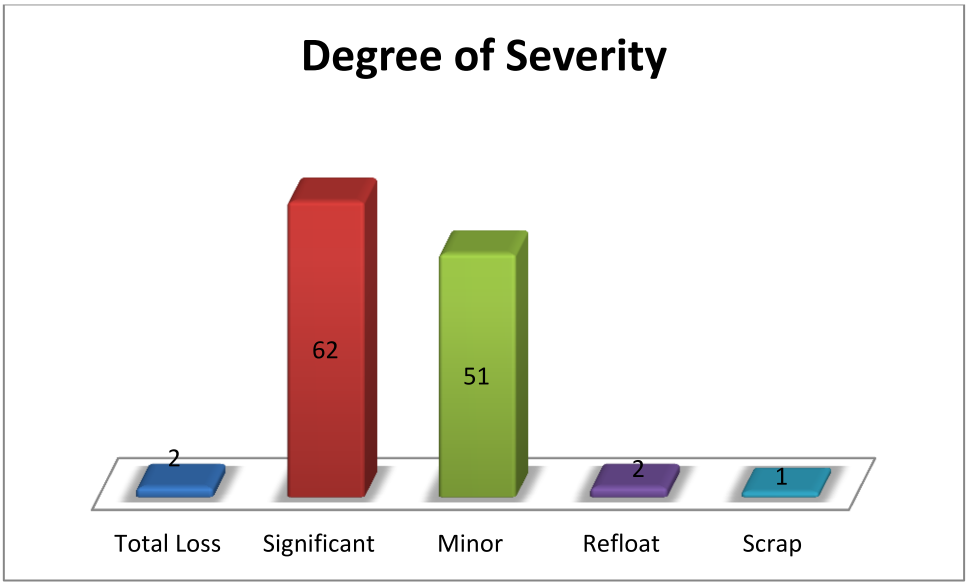


Figure 5.6: Features of LOWI and severity for Hull Damage

Wrecked/Stranded

The last but not least category of NASF casualties is the category that contains incidents which led to a wreck or stranding. As shown in Figure 5.1, its percentage is about 23% and an analysis in the abovementioned terms shows some useful conclusions too.

As far as weather data concerned, about 53% of them were missing. But the rest of them contribute to the result that heavy weather was noticed in 62% of studied reports, something that does not make sense as the heavy weather usually block the efforts of the crew to face a problem and help any failure to develop dangerously for the seaworthiness. Moreover, thirty-one (31) out of forty-five (45) (69%) investigated reports indicated that failures happened during the day.

The other two points that evaluated were the loading condition and the operational situation of ships at the time of the casualty (Figure 5.7). About 80% of the accidents had occurred ship was loaded (36 incidents). The high percentage that presented is due to the fact that a full of cargo ship is handled very difficult and the crew cannot face the hazards efficiently. Another 71% of the incidents that led to a wreck or stranding happened during a voyage.

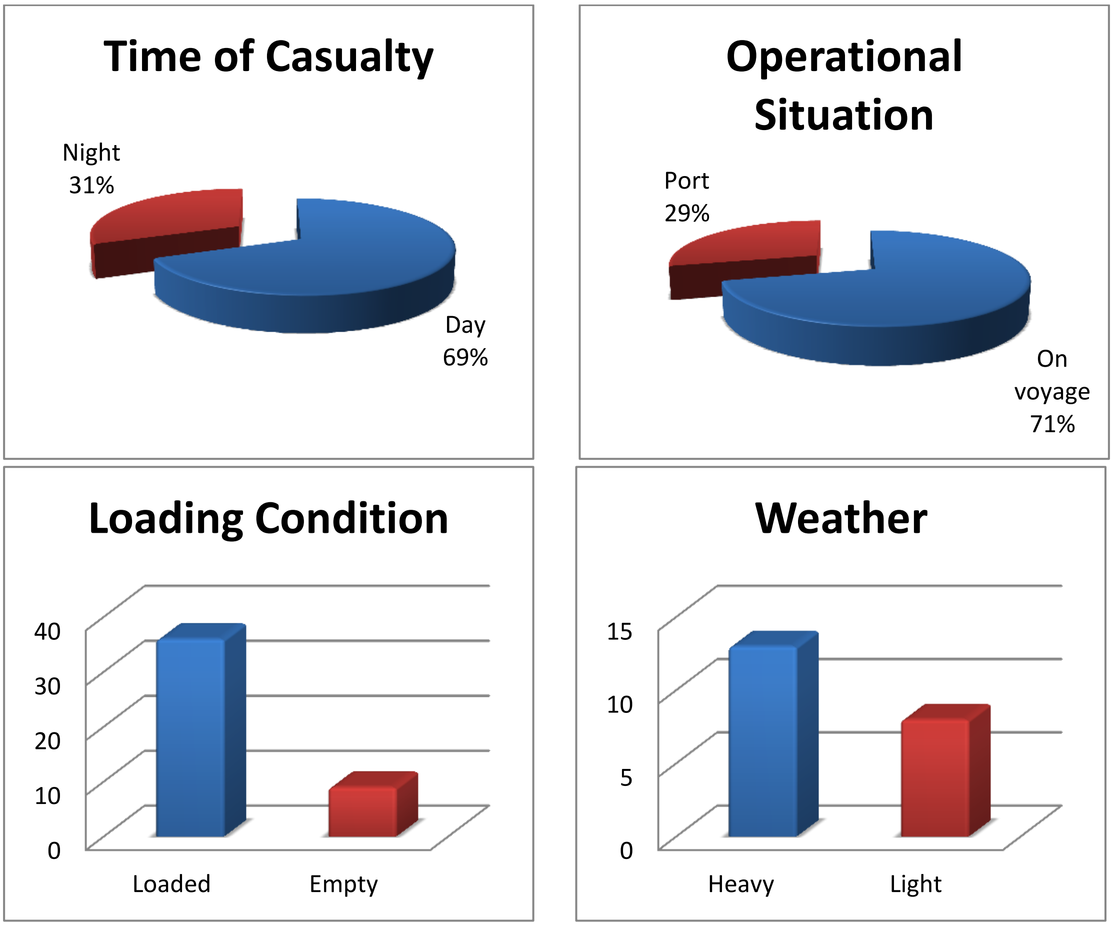


Figure 5.7: Features of time, operational situation, loading condition and weather for Stranded/ Wrecked

An important outcome of the analysis for Stranded/Wrecked casualties is that LOWI observed in eleven (11) out of fifty-six (56) cases (19.6%). It must be mentioned that water ingress in these cases either appeared prior to the incident because of a structural failure or after the stranding. In all occasions, structural failure was the initial point of this type of casualties.

Finally, the last factor that was taken into consideration was the severity of each accident. The investigation showed that five (5) out of fifty-six (56) occasions (9%) ended up with the total loss of the ships and approximately twenty (20) cases (35.7%) were characterized as "Significant" by the database. This means that wrecked/stranded casualties are assumed as very hazardous accidents for people's lives and environment's pollution.

Figures 5.8 and 5.9 present the statistics of water ingress and severity of studied reports for Stranded / Wrecked that derived from structural failure.

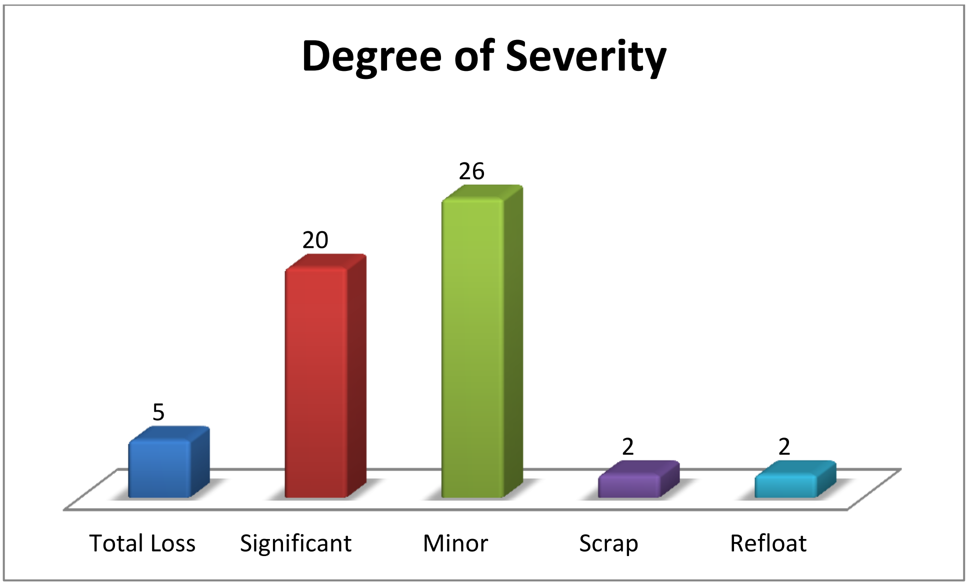


Figure 5.8: Severity of casualties in percentage

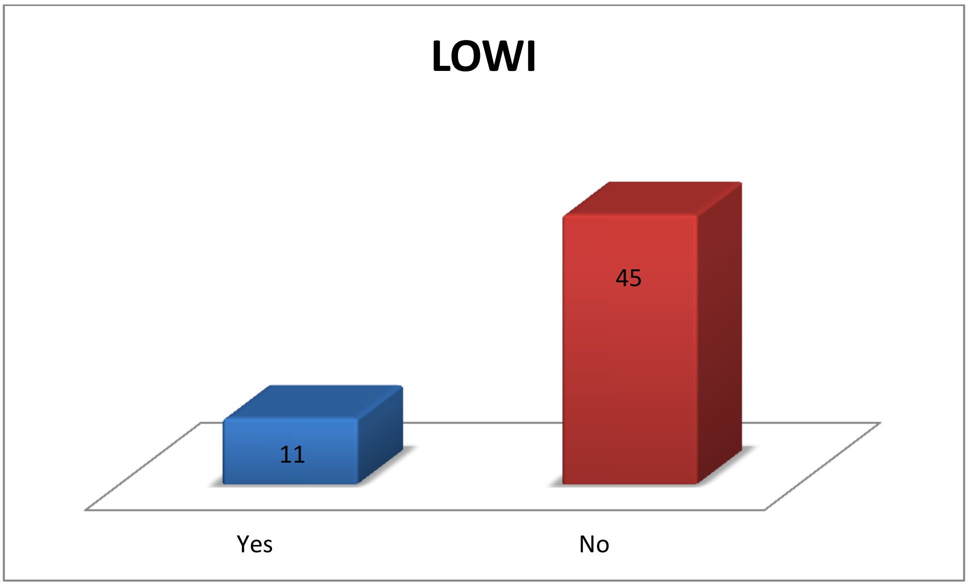


Figure 5.9: Loss of watertight integrity

5.2 Specialized Analysis of NASF

Present analysis contains an advanced research for RoPax accidents. In current chapter, statistics are going to be presented as a background of the main analysis (Risk Analysis) which occurred with the respect to historical data. However, the above results are not only assistive but they have high significance for the comprehension of NASF too.

It has to be highlighted that existing data for NASF incidents were distinguished in two categories with regards to GT. The following classes are:

- RoPax ships of 4,000 GT and below. As it can be seen, small (0-1,000 GT) and medium (1,000-4,000 GT) categories were merged to one due to the fact that there were not adequate amount of data so as to extract safe upshots for each category separately. Although ships of 1000 GT and below usually excluded from similar studies because of their engaging on short crossings and their open type configuration, it was decided to take them into consideration due to the fact that it was assured that vessels of current fleet were mostly closed- type configuration and part of their cargo were not exposed to weather. Also, as it was mentioned before, RoPax vessels that were taken into consideration were consisted of 200 GT and above. It must be mentioned that for the continuation of specific thesis, wherever 0-4,000 GT is shown, it is implied that the least value of ships' GT considered, was the value of 200 GT.
- RoPax vessels of 4,000 GT and above. Large category of RoPax fleet had to be studied because of their transferring a wide number of cargos and the presence of human life as lots of passengers are transported in these ships.

Another restriction that was done, so as to be ensured that current analysis would be constructive for maritime community, was in relation to the time period that accidents had occurred regardless of the year of ships' built. The selected period was 1985-2016 due to the fact that the combination of a contemporary fleet with respect to a satisfactory number of casualties, it had to be achieved.

Furthermore, a classification regarding to the nature of Non Accidental Structural Failure occurred. The first class contains NSAF accidents that had as a cause cracks, dents or fractures and the second one includes casualties with corrosion's presence. Certainly, as it has been already mentioned above, these incidents occurred either in the hull or in tanks and pipes.

Of course, it goes without saying that four categories were derived by above restrictions and classifications. The following categories are specified:

1. RoPax ships of *4,000 GT and below with the presence of cracks, dents and fractures (Small class with fatigue failure).*

2. RoPax ships of *4,000 GT and below with appearance of corrosion (Small class with corrosion).*
3. RoPax ships of *4,000 GT and above with the presence of cracks, dents and fractures (Large class with fatigue failure).*
4. RoPax ships of *4,000 GT and above with appearance of corrosion (Large class with corrosion).*

The casualty reports are investigated so as the distribution and the amount of every category to be found. It can be noticed by the Table 5.2 and the Figure 5.10 that the majority of the incidents pertain to the small class with fatigue failure with the significant percentage of 38%. The following category is the large class with fatigue failure that its percentage reaches to the 26% of total failures. As a result, it is obvious that fatigue failures happen more often in smaller ships. In addition, a remarkable outcome is the proportion between fatigue and corrosion failures differs a lot as corrosion failures constitute only the 46% of total incidents.

Classes	Number of Incidents	Percentage (%)
Small Class with Fatigue Failure	77	38.5
Small Class with Corrosion Failure	39	19.5
Large Class with Fatigue Failure	52	26
Large class with Corrosion Failure	32	16
Total	200	100

Table 5.2: The distribution and the amount of failures in the specified classes

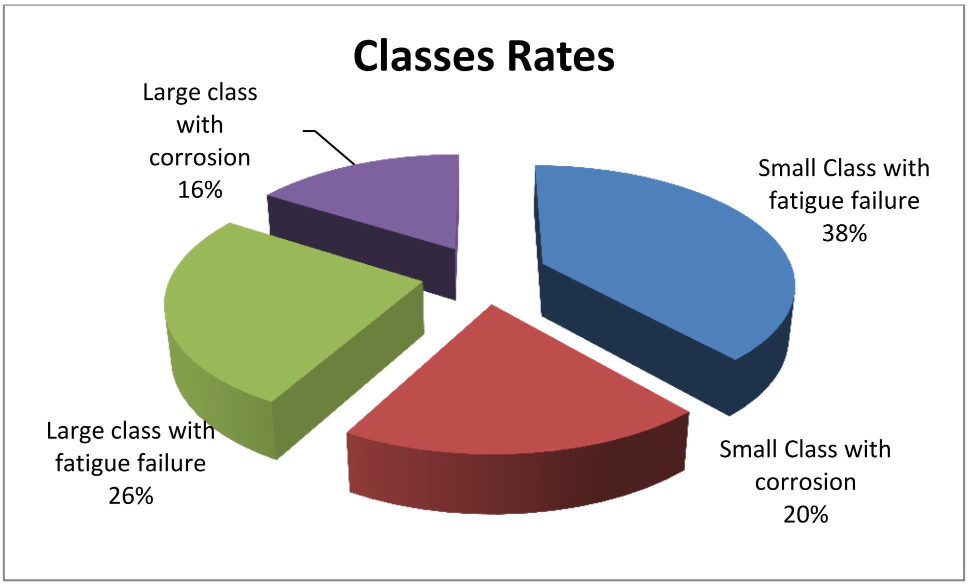


Figure 5.10: The distribution of failures for specified classes

For each category a statistical study was occurred with respect to terms that have already mentioned and results in relation to weather, the operational situation, loading condition, the severity of incidents, the LOWI, the time and the type of casualties are presented for every specified class.

Ships of 4,000 GT and below with fatigue failure

Incidents in this category represent about 38% of the identified accident categories, as it is shown in Figure 5.10. For all casualties, information for their type was given and it can be seen by Figure 5.11 that a high amount of them led to Stranding or a Wreck (26%) and only 18% of them had as a sequel a Foundering.

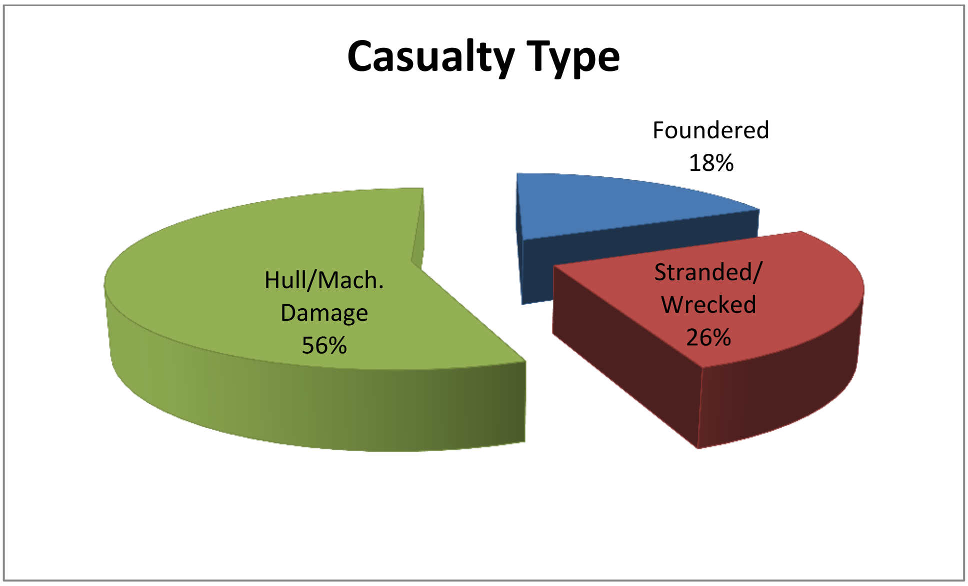


Figure 5.11: Proportion of casualty's type for small class with fatigue failure

For about 33% of the accidents information with respect to the day and the weather were available. But it is reprehensible that 69% of the incidents occurred in heavy weather, something very logical if someone considers the sizes of current ships (Figure 5.12). Also, the majority of them happened during the day as 65% of the existing data mentioned that the appearance of the failure was during the day.

For all sample of specific class, an operational situation and loading condition of ship was specified (Figure 5.12). Accordingly, *52* out of *77* cases (68%) found to be on voyage during the casualty and that is another reason of the high percentage of foundered casualties in this category as assistance it was difficult to be given. Moreover, ships were usually Loaded (67%) and the manipulations for the confrontation of the casualty had an additional difficulty.

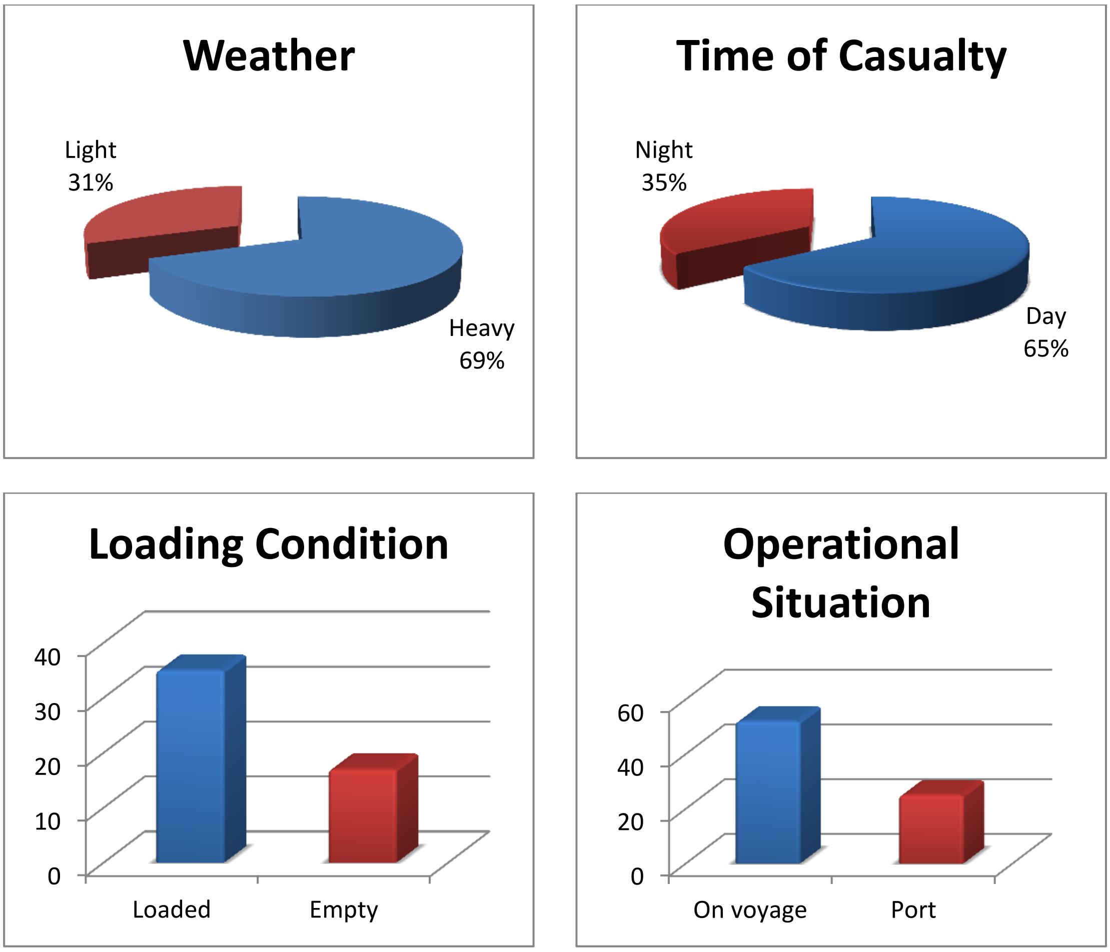


Figure 5.12: Features of weather, day, loading condition, operational situation for small class with fatigue failure

Ships of 4,000 GT and below with corrosion failure

By analyzing casualty reports which resided in current class, it was observed that corrosion failures do not usually end up in Foundering as its percentage is only 12.8% or in a Stranding/ Wreck incident which proportion is about 18% (Figure 5.13). It can be suggested that corrosion failures although that may be of big severity, they do not usually cause the sinking of a ship.

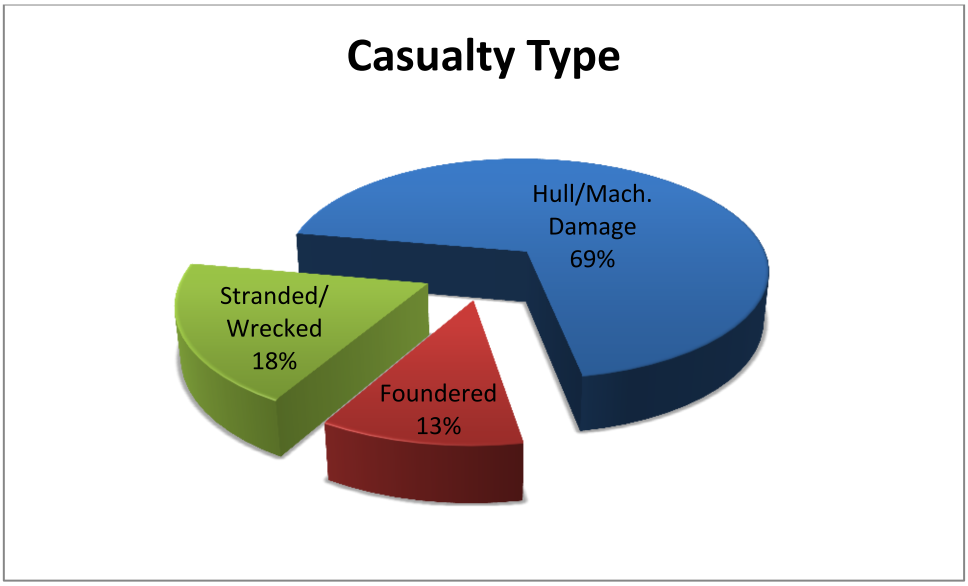
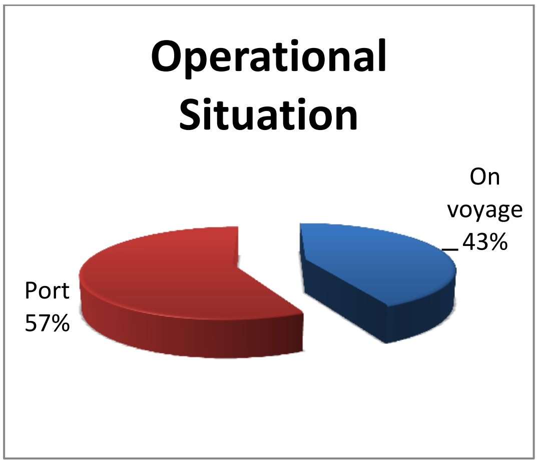


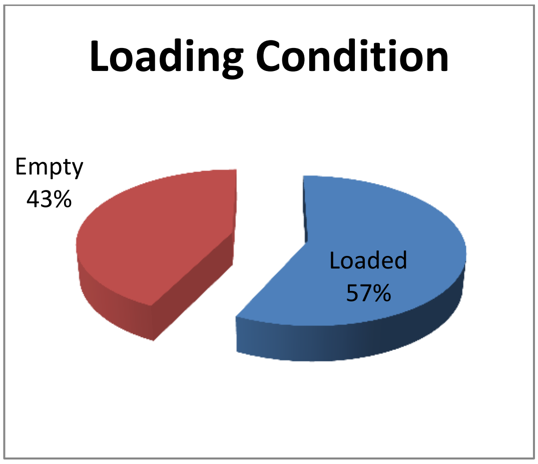
Figure 5.13: Allocation of casualty's type for small class with corrosion failure

In *37* out of *39* of concerned reports, an operational situation and loading condition were observed. In many respects, specific sample can conduce to the creation of some perceptions for the ship's situation at the time of the casualty. By the interpretation of Figure 5.14, it can be noticed that about 57% of specific sample occurred corrosion incident while ship was at port. That can be justified by the inactivity of some ships and the consequently neglect of a ship's care. Additionally, the mark "Loaded" was enumerated in 57% of the percentage at the time of accident.

For only 16% of incidents, data were existed with respect to the weather and all of them had signature for heavy weather so it has not to be presented as the sample is of low quantity.

Finally, database was analysed in relation to the time that casualty occurrence became and the results were that most of them observed during the day (82%), as Figure 5.12 represents.





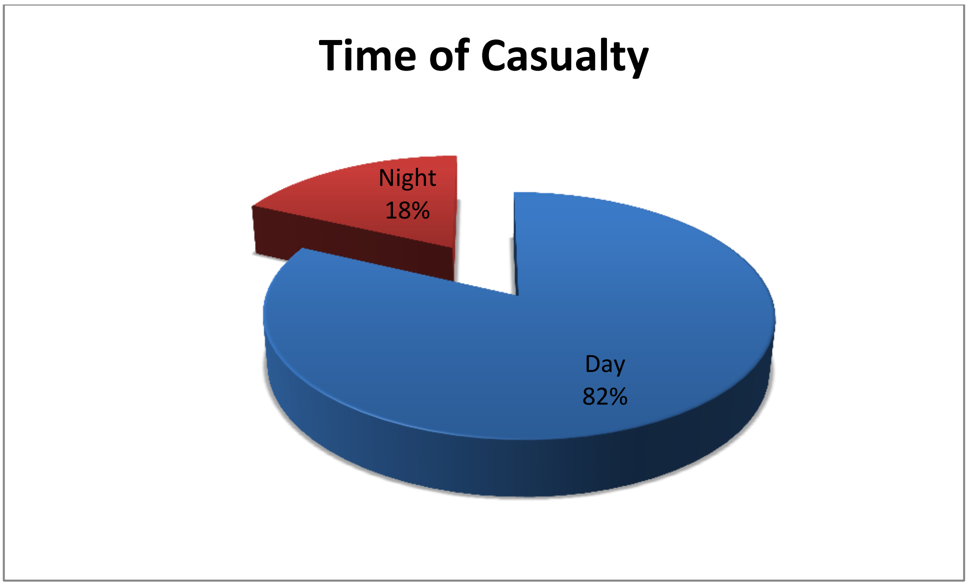


Figure 5.14: Features of operational situation, loading condition and the time of casualty for small class with corrosion failure

Ships of 4,000 GT and above with fatigue failure

The investigation of this category revealed the differences between small category of GT with fatigue failure and large category of GT with fatigue failure. As it has already observed by Figure 5.11, fatigue failures in small class possibly lead to foundered or wrecked. On the other hand, by Figure 5.15, someone can reach the conclusion that the possibility of Foundering reduces a lot and it is equal to 7.7% while Stranded/Wrecked reaches a value up to the 36.5%. Therefore, it is an undisputed fact that large Ropax ships incur lesser possibility for significant damage.

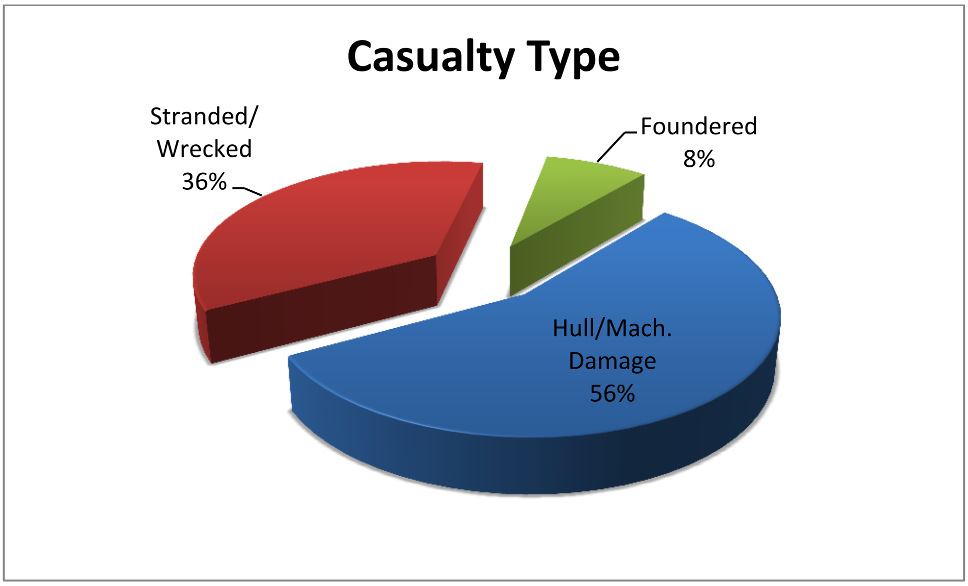


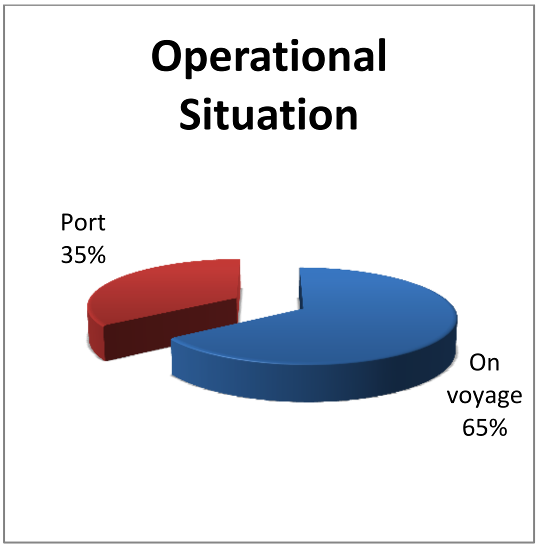
Figure 5.15: Percentage of each casualty type for the large class with fatigue failure

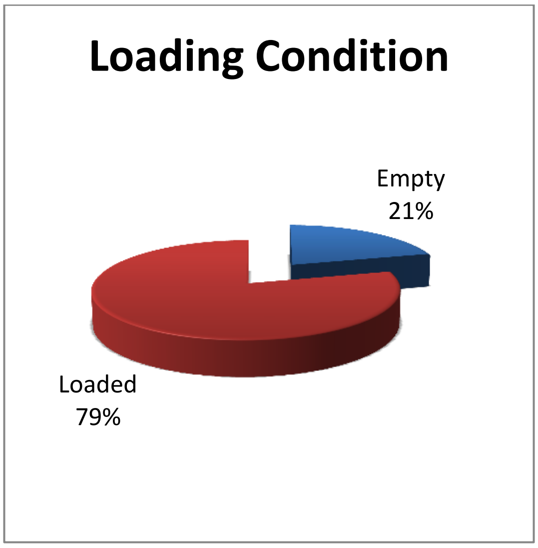
Reports of the database that had described current category were evaluated with respect to the operational situation and the percentage of existing data for specific variable was absolute. The outcome of Figure 5.16 can convince everyone that fatigue failures occur by approximately 65% while vessels are on voyage if Figure 5.12 is reconsidered too.

In 85% of the records the loading condition is specified. Of these, most of the fatigue failures happened in a “Loaded” ship (79.5%). This factor goes with the trend in the small class with fatigue failure too, even though the percentage in large category is higher.

As far as time of the accident concerned, data that obtained from database were inadequate because there was only 17% of the total sample. So it would not be constructive to present the outcomes.

Eventually, a graph with regards to weather is developed on the basis of 38 out of 52 casualty reports. It is obvious that 56% of existing data for weather described weather condition as “Heavy” (Figure 5.16). Similar to the small category of fatigue failure the percentage of adverse weather conditions is significant. However, it must be highlighted that accidents in current category do not affect so much by weather conditions. Explanation in this is that while ship particulars are increased and capacity of passengers is increased too, the regulations of a ship structure are stricter.





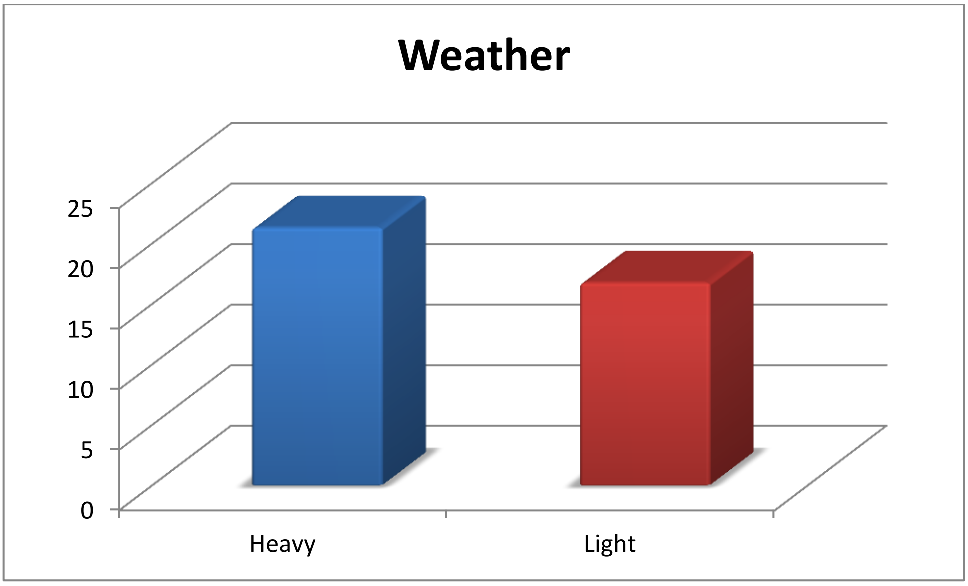


Figure 5.16: Features for operational situation, loading condition and weather for large class with fatigue failure

Ships of 4,000 GT and above with corrosion failure

The statistics of this class were developed on basis of thirty-two (32) reports. Initially, the types of casualty were recognized by the investigation which held (Figure 5.17). It can be noticed that a wide number of incidents led to Stranded/Wrecked situation (31.3%) and a valuable percentage of current incidents had as a consequence the Foundering of the ship (10%). It can be observed by Figure 4.17 that the proportion of a Stranding is much higher than the corresponding one for smaller ships (Figure 5.11). By comparing these two graphs, the outcome that foundering's reduction is minor can be visible and corrosion failure seems to be regardless of the size and capacity of ship.

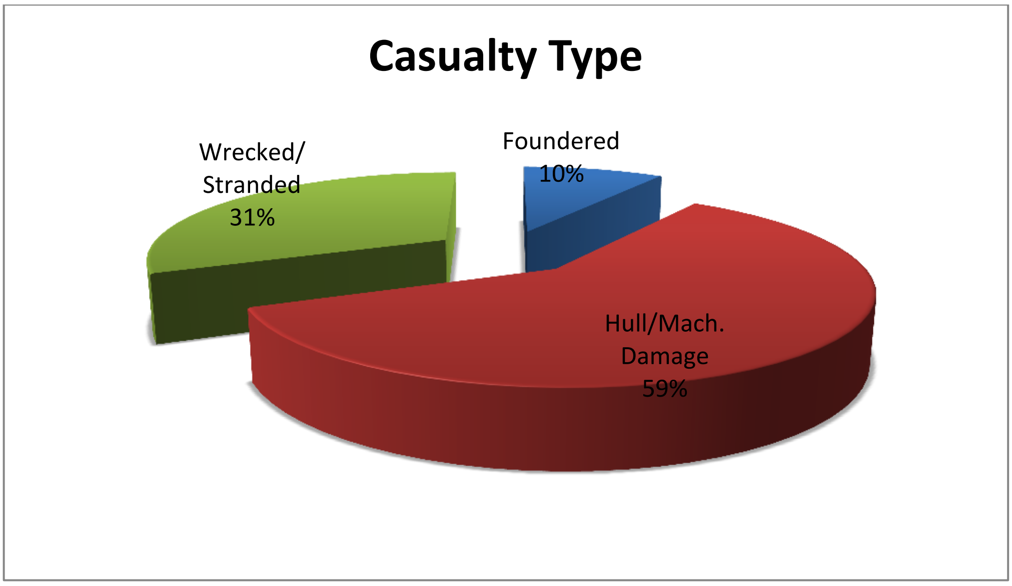


Figure 5.17: Percentage of casualty's type according to the specified class

In twenty-eight (28) out of thirty-two (32) cases, data for ship's operational situation were given and it can be easily realized that about 57% of specific ships were on voyage (16 casualties) at the time of the incident (Figure 5.18).

For about 72% of the accidents information in relation to the loading condition were given by the database. So it was feasible to be found out that in 78% of the casualties that occurred, ship was "Loaded" and that can be seen in Figure 5.15.

It must be remarked that there were not adequate information so as to take in consideration the factors of the weather and time.

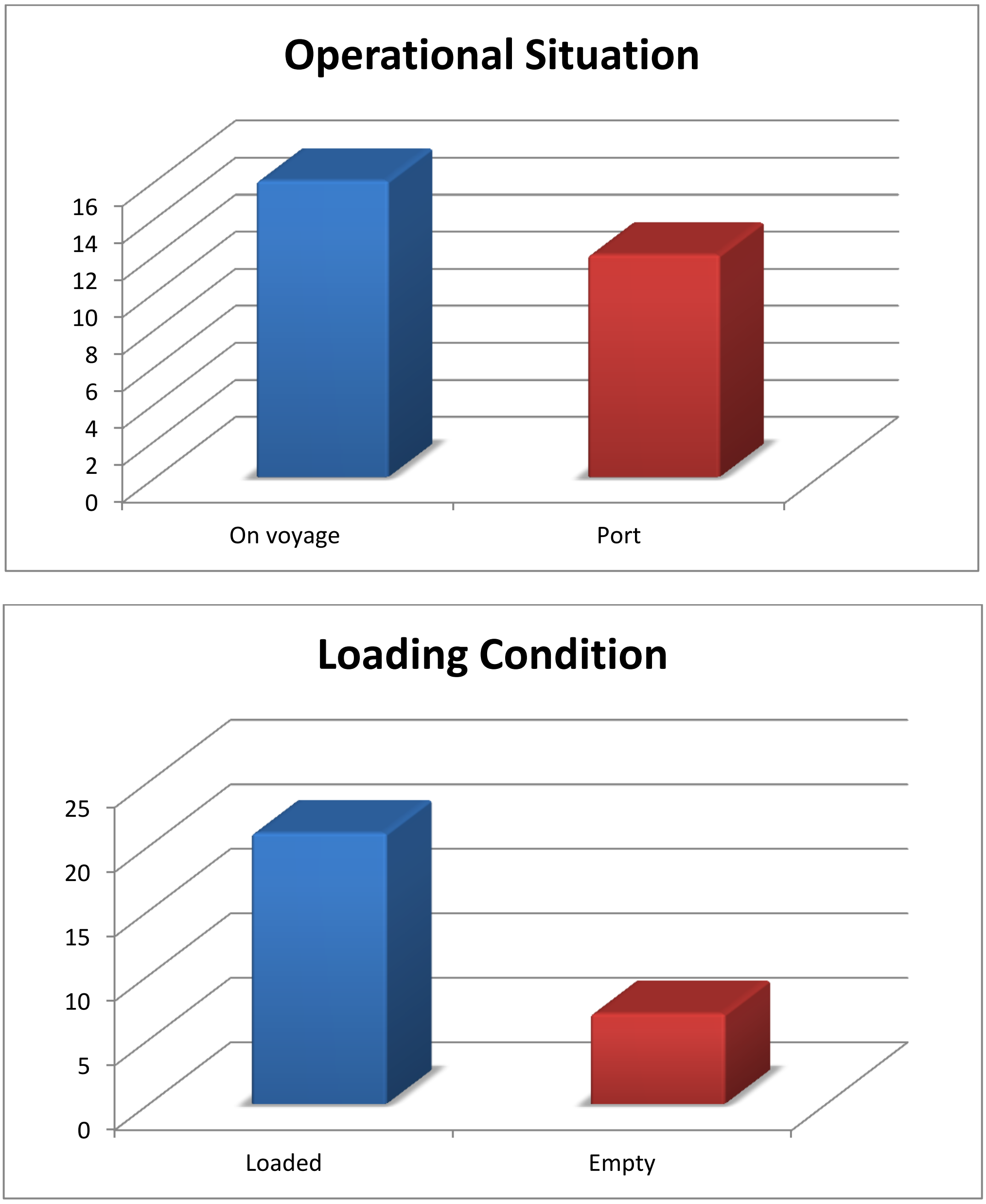


Figure 5.18: Features of operational situation and loading condition with respect to the large class with corrosion failures

6. Risk Analysis of Non Accidental Failures

6.1 Risk Model

In this chapter the development of the risk model is presented in detail. The current model is developed by means of event trees and with respect to NASF incidents. As specified statistical analysis occurred in 4 categories, so Risk Model developed for each of the following categories of RoPax ships:

- RoPax ships of *4,000 GRT and below with the presence of cracks, dents and fractures (Small class with fatigue failure).*
- RoPax ships of *4,000 GRT and below with appearance of corrosion (Small class with corrosion).*
- RoPax ships of *4,000 GRT and above with the presence of cracks, dents and fractures (Large class with fatigue failure).*
- RoPax ships of *4,000 GRT and above with appearance of corrosion (Large class with corrosion).*

As a consequence, 4 events trees are developed for that Risk Model considers the consequences in relation to the safety, environment and property. It had to be noticed that one event tree occurred for each specified class with the percentages that arose, using them for the branch probabilities of the respective scenarios on the event tree.

Non Accidental Structural Failure risk model based on 200 casualty reports, which all information that was needed, were available. The required information about current analysis was concerned about 6 events. Top event for each event tree was set the possibility of a Non Accidental Structural Failure. Subsequent events were: the starting point, the location, progression of damage, LOWI of each ship that was involved in the incident and the degree of severity for each casualty.

6.2 Description of Event trees

6.2.1 Small Class with Corrosion

The generic event tree of current category, which based on the seaweb database for the period of 1985-2016, is presented in Figure B.1 (Appendix B). The investigated data and the results are mentioned:

Intermediate Events

Corrosion occurs in hull

Regarding the occurrence of corrosion on the hull of the ship, thirty-one (31) out of thirty-nine (39) of the reported accidents (79.5%) for RoPax ships were observed with a failure during the considered period (1985-2016). The other 20.5% of the examined casualties related to corrosion concerned failures in the piping system or tanks.

Starting Point:

As far as the initial starting point of the failure is concerned, 38.71% were noticed to the bottom shell and an equally vital percentage of 29.03% observed on the side shell. Moreover, five (5) failures (16.13%) happened at Exterior Deck, two (2) on the floor and inner bottom (12.90%) and one (1) on the Interior Deck (3.23%). Finally, only four (4) cases were related to tanks and pipes.

Location:

According to the area of the ship where the failure was located, from twelve (12) incidents that originated at the bottom shell, six (6) were presented in the aft area (A.A.) while five (5) in the cargo area. From the examined incidents with failures that originated at the side shell, 44.44% were located in the aft area of the ship. Corrosion in the Interior Deck appeared only to the A.A. As far as exterior deck concerned one (1) occasion out of the five (5) incidents (20%) included a failure on forepeak (F.P) while the other four (4) were located in the aft and cargo area. Contrary to the hull deterioration, corrosion cases regarding tanks and pipes had a direct link with the A.A of the ship.

Progression of Damage:

The probability of the vessel to incur Cross Section Failure depends heavily on a high rate from the location and the starting point of failure. For the bottom shell, the probability of a Cross Section Failure was estimated at about 60% for the cargo and aft area. While Cross Section Failure in the side shell was observed only in the cargo area and its percentage was 33.33%. Furthermore, only in one (1) additional case observed progression of damage with failure of cross section and concerned the Inner Bottom. On the remaining cases, there was not progression of damage except for tanks that all the recorded failures led to leakage and pipes that leakage reached to the percentage of 75% (*3* out of *4*).

Loss of Watertight Integrity:

LOWI cases comprised about 41% of the acquired data, which is considered a high percentage if it is taken into account that RoPax ships transport passengers. The examination of the accident data led to the conclusions that a Cross Section Failure almost always causes a hull breach and LOWI is mostly connected in bottom failures. Regarding side shell failures, two (2) cases were marked as LOWI, one (1) at the aft area and one (1) at the forepeak area. Additionally, no failures in the piping system occurred with LOWI.

Degree of Severity:

All cases of flooding incidents that were caused by deterioration of the hull are classified as “Significant”. It should be noted that all the Failure of Cross Sections in the constructed Event Tree, lead to the Loss of the ship. Typically, the reported casualties that were accompanied with LOWI are classified as “Significant”. In addition, leakages in the piping system are stated as “Significant” and leaks in tanks are classified as “Minor”. Overall, “Significant” cases comprise 36.52% of the total number of incidents, “Total Loss” 20.50%, “Scrap” and “Refloat” 2.56%, while “Minor” cases represent the 37.86% of the incidents.

In Table 6.1 the values of the event trees are summarized and expressed collectively, while in Figure B.1 event trees are developed.

Consequences

Loss of Life

For the consequence category “Small Class with Corrosion”, no fatalities were reported in the accident database. This may be an indication that corrosion failures for RoPax ships under 4,000 GT do not result loss of life.

Environmental Impact

Although casualty reports contained information about the occurrence of the pollution to each incident that was recorded, precise values of the spill quantities were not given for all the occasions. So, having researched tanks capacity for each ship that involved in a casualty following by pollution, rates of spilled oil were found. In this category, the exact quantity of the pollution was recorded for *1* “Significant” incident (*3*tonnes). The other quantities calculated with the aforementioned method. For the other “Significant” incident the oil spill was estimated *8.64*tonnes as tank capacity of the ship was multiplied with the percentage of 0.02%. As a result, taking into consideration the probability of these two “Significant” incidents to occur in this category (2.564%) and the amounts of the spills, the risk contribution of the oil that can be spread is 0.3tonnes. Contrariwise, having investigated tank capacity for the ship that lost and caused pollution, it was assumed that the spill contained *122*tonnes of oil (it was taken a 30% of the percentage of ship’s tank capacity). So, the risk contribution for spread oil that can be spilled by “Total Loss” is about 3.13. Eventually, the Total Potential Environmental Impact (PEI) can be calculated as the sum of the two degree of Severity and it was calculated about 3.43.

Damage to property

In the present state of development risk model, an estimated 20.5% of the incidents led to ship’s total loss while refloat and scrap occurred only for about 2.56% of current fleet. By DNV-GL’s research is perceivable that if someone wants to acquire a new ship of 4,000GT and below must invest an amount that is given by a predefined formula. So, if the percentage of each scenario for “Total Loss” is combined with the derived amount of money which depends on Gross Tonnage of each ship that was lost, the Potential Damage to Property (PDP) can be estimated about 3.783. Refloat cost is derived by a percentage of 25% of the newbuilding price and the possibility of occurring refloat on each scenario. As a result the cumulative risk of the cost for "Refloat" is 0.158. Furthermore, scrap's price depends on the lightweight of the ship and for such category the average lightship (LS) was found by database and was multiplied with the price of steel in current period. The average benefit of scrap for specific class and incidents reaches to 0.4 million euros while the average cost to the property is estimated with the price of a newbuilding minus the value of scrap. It derives that the PDP for "Scrap" is 0.158. The total potential property to damage is estimated 4.139.

6.2.2 Large Class with Corrosion

Figure B.2 (Appendix B) shows the generic corrosion event tree which includes RoPax ships that their gross tonnage is higher than 4,000 GT. Outcomes for specific category presented below:

Intermediate events

Corrosion occurs in Hull:

Casualty data owing to this class indicate that twenty four (24) out of thirty-two (32) accidents (75%) appear in hull whilst the remaining ones were due to tanks and pipes (25%).

Starting Point:

For hull failures ten (10) out of twenty-four (24) cases (41.67%) were noticed in side shell and about 20% of these incidents appeared in bottom and the exterior Deck. Accidents that were not observed in hull are allocated at 62.5% for pipes failures and 37.5% for tanks deterioration.

Location:

As far as hull structural failures concerned, a rate of 55.5% contains incidents that occur in A.A. whereas 30.5 % represents the failures that located in cargo area. As a consequence, 14% of them were observed at F.P. It must be noticed that 60% of bottom and side shell failures appear in the aft area. Conversely, tank and pipe failures were remarked only to A.A.

Progression of Damage:

It can be easily derived by the event trees that failure of cross section occurs in hull's deterioration with the possibility of 12.5% and an estimated 87.5% has not progression of damage. Contrary to that, incidents that refer to tanks and pipes do not present any possibility for ship's failure of cross section and they are characterized by a leakage or a non-spread damage. Leakage is the major cause of these types of accidents and its influence is vivid by the percentage of 87.3%.

LOWI:

Flooding cases were observed at the percentage of 31.2% and occasions without ship losing its watertight integrity is the 68.8%. It worth to be mentioned that corrosion in bottom led to the breach of the hull in all cases and inner bottom, floor, tanks, exterior and interior deck are not suffered by flooding. Finally, pipes produced flooding when they fail with a percentage of 40 %.

Degree of Severity:

The majority of corrosion accidents of this category are of “Minor” severity (53%) following by casualties with “Significant” severity (37.6%). Interest presents the fact that the rates of “Total Loss” (6.3%) and “Refloat” (3.1%) are low. Furthermore, total loss and refloat are noticed only in bottom shell and side shell, something reasonable and common.

Consequences

Loss of Life

Neither in this category of RoPax ships occurred fatalities due to corrosion and as a consequence it can be presumed that corrosion casualties are not usually lead to dangerous accidents for the human life.

Environmental Impact

The current analysis is resulted some conclusions with respect to the environmental pollution. In four (4) out of thirty-two (32) incidents (12.5%), pollution appeared, in which only for one (1) of them recorded data for its extent were given. The specified oil spill was about *2.5* tones for a “Significant” incident and the other quantities for spread oil in this degree of severity were estimated as it has been already mentioned (*1.1tonnes*, 3tonnes). The risk contribution of the extent of spreading oil for “Significant” incidents in relation to the percentage of each significant casualty (3.125%, 3.123%, and 3.125% respectively) is 0.2. The last recorded pollution was for a “Total Loss” casualty and its oil spill was assumed *128.8*tonnes because of the tank capacity of the ship. So, the PEI for this “Total Loss” (3.12%) is about 4.02. It derives that the aggregated PEI is 4.22.

Damage to Property

Based on the casualty data reports and relating total losses and refloat of ships that are recognized, with the predefined terms, it derives that cost’s cumulative risk is 3.15 owing to the loss of ship (6.3%) and 0.372 for ships that incur “Refloat” (3.1%). So, it has to be remarked that the total cost with respect to damage to property is 3.522.

6.2.3 Small Class with Fatigue

A developed event tree is listed in Figure B.3 (Appendix B) with regards to the NASF incidents which occur due to fatigue and a wide variety of results and conclusions are mentioned below:

Intermediate events

Fatigue occurs in Hull:

In seventy-four (74) out of seventy-seven (77) cases (96.1%), it was specified that casualties occurred in hull. Although this percentage seems to be excessively high, it is very reasonable as tanks and pipes do not stress by a heavy way with loads which may stress them and contribute to a structural failure.

Starting Point:

In case of hull failures nearly 54% are located in the side shell and circa 27.03% appear in bottom. Of those failures that did not occur in hull, all of them happened in tanks.

Location:

For the investigated data which represent casualties that occurred in hull during 1985-2016, it was evaluated that 31.1% of them were located in forepeak, 36.5% appeared in cargo space and 32.4% happened in A.A. Contrariwise, fatigue failures that their starting point was found in tanks, observed to be only in the aft area.

Progression of Damage:

It can be noticed by Figure B.3 that about 24.2% of specific incidents led to failure of ship's cross section. Furthermore, 75.8% are not characterized by subsequent damage. It comes without saying that a leakage is not reported in the whole current fleet.

LOWI:

A proportion of 56.82% of the accidents that are examined seems to have a breach in the hull. It is obvious that ships with 4,000GT and below have an essential possibility to lose their watertight integrity, something extremely hazardous for ships that their main cargo are humans.

Degree of Severity:

An imperative outcome of the research for specific category of RoPax ships is that 24.67% of current ships suffered from total Loss, whilst 42.68% of them were remarked by database as "Significant". Also, "Scrap" remarked in 2.6% of the occasions and the remaining percentage (30.45%) was due to "Minor" casualties.

Intermediate events

Loss of Life

In total *11* fatalities and *9* severe injuries were reported. The maximum number of fatalities which occurred in one incident was 5, while the majority of injuries (*8*) happened in one accident. All fatalities are accompanied with a Total Loss. So for Total Loss if the 1 serious wounding which appeared in a total loss is considered too, the total risk contribution of Potential Loss of Life (PLL) is estimated 0.150. The other 8 injuries with the assistance of "Significant" severity percentage of specific accident can contribute to the conclusion that PLL for "Significant" category was 0.001. As a consequence, the total risk contribution for Loss of Life of this category is about 0.151.

Environmental Impact

For only *3* incidents oil pollution was noticed and no data for the extent of the oil spill were given. All occasions were characterized by the total loss of the ship and with the specified method, oil spills were calculated (124.7tonnes, 55.2tonnes, 132.5tonnes). Given the possibility of Total Loss occurrence in these 3 categories the risk contribution of spill estimated about 4.78 tonnes of oil spill.

Damage to Property

The potential cost for the property in the degree of severity "Total Loss" found to be 4.755. While "Scrap" estimated with respect to the average lightship of a typical RoPax in specific category of GT and its average value was found about 0.8 million euros. As a consequence, the PDP cost of "Scrap" for this class can be calculated and it is 0.154. It is obvious that the full potential damage to property is about 4.909.

6.2.4 Large Class with Fatigue

Current risk model is developed for RoPax ships that their GT is 4,000 and above with respect to fatigue failures. The results of this model are expressed in Figure B.4 and are listed below summarily.

Intermediate events

Fatigue occurs in Hull:

Following the investigation for casualties that their cause was the fatigue, it was found that fifty (50) out of fifty-two (52) failures (96.15%) appeared in hull's ship. This percentage keeps up with the proportion of the small class, something which shows the tendency of fatigue failures to occur in a high rate to the hull.

Starting Point:

It is obvious, by Figure B.4, that hull failures appear in a significant percentage (68%) in the side shell. Other initial starting points of failures have minor percentages which are distributed with small differences. Moreover, the trend that only the tanks are observed to have as a cause the fatigue for the non-hull failures is confirmed and in this category.

Location:

By calculating the possibilities for each of three locations that have already been specified, it can be seen that the vast majority of the incidents in this category occur in aft area (44.2%). On the other hand, 32.7% of the investigated data in relation to the location indicates the possibility of the occurrence in the cargo space, while the remaining 23.1% refers to the forepeak location.

Progression of Damage:

Figure B.4 indicates that failure of a ship's cross section may occur in percentage of 11.45% of all incidents that happened in concerned fleet. Another possibility of 3.85% represents the possibility of a leakage and it goes without saying that leakages derive only from the tanks. It must be noticed that the percentage for the failure of cross section is immensely lesser that the observed one for the small class with fatigue. The reason of this is that here ships are bigger and because of the big routes that follow, they must be compatible with stricter regulations.

LOWI:

By the analysis of the event tree with respect to the watertight integrity, it can be perceivable that for about 1 out of 2 cases (50%), loss of the watertight integrity is observed. Another point which must be noticed is that even though the exterior deck, interior deck and floor are not recorded with a breach in hull or tank, the percentage of the LOWI is so vital. An explanation of this is that in specific starting points of failure, there were underreporting and no adequate data were given so as to reach in conclusions about the real percentage of LOWI.

Degree of Severity:

This event gate indicates the possibility for each incident to be characterized with respect to severity and it is affected by a lot of means from the LOWI event and progression of damage. As "Minor" named about 36.5% of concerned fleet and these incidents are derived by those which are not observed a LOWI and a failure of cross section. Conversely, "Total Loss" (7.7%) and "Refloat" (3.8%) presented only when a failure of cross section has already occurred. In addition, incidents which recorded as "Significant" (48.2%) are mostly derived by those that there were occurred a LOWI but without a failure of cross section. Eventually, "Scrap" is about 3.8% of the total percentage.

Consequences

Loss of Life

Due to the fact that ships in this category travel in open seas or accomplish voyages with a respectful number of passengers, it is given an additional emphasis on the safety. As a result only 7 minor injuries occurred owing to fatigue failures incidents. All of them appeared in a “Significant” incident. Combined with the percentage of the specific degree of severity, it was arisen that PLL for “Significant” casualties in this category is 0.0013.

Environmental Impact

Information about the occurrence of pollution was given in all incidents. After a critical review, it was found that in *3* occasions pollution happened, but for no incident the exact data, for the oil spill, was described. For these *3* casualties, quantities of oil spill were calculated with respect to tank capacities of each ship and their value were for the Total Loss (87tonnes, 144tonnes) and for “Significant” (7.5tonnes). As a consequence, the PEI of total Loss situation is 4.44 while for “Significant” severity of incidents the potential oil spill is estimated about 0.14. The total risk for PEI is about 4.58.

Damage to Property

For each casualty, an estimation with respect to the damage to the asset occurred. Analytically, in the case of “Total Loss” the price for a newbuilding for each ship was assessed with respect to the Gross Tonnage. In combination of this value and the distribution of “Total Loss” severity for concerned category of ships and accidents, the cost for ship owners was calculated to 4.235. On the other hand for “Refloat” and with multiplying the price of a newbuilding ship with a rate of 25%, it became feasible to calculate Refloat costs. So the PDP for “Refloat” situations of specified class reaches to 0.646. As far as the potential cost of “Scrap” is concerned with respect to the Lightship of ships that occurred “equals to 1.51. The total PDP for current category reaches 10.094.

6.3 Evaluation of Outcomes

Although adequate effects can be emerged by the description of the Event Trees, it was decided as necessary to group and compare the results depending on the kind of failure and the size of ships. So, tables and graphs are developed with respect to the consequences of the incidents (losses of life, environmental impact, damage to property).

Initially, in Figure 6.1, 6.2, 6.3 the aforementioned consequences for each specified category are shown so as to comprehend the differences and the outcomes of Risk Analysis.

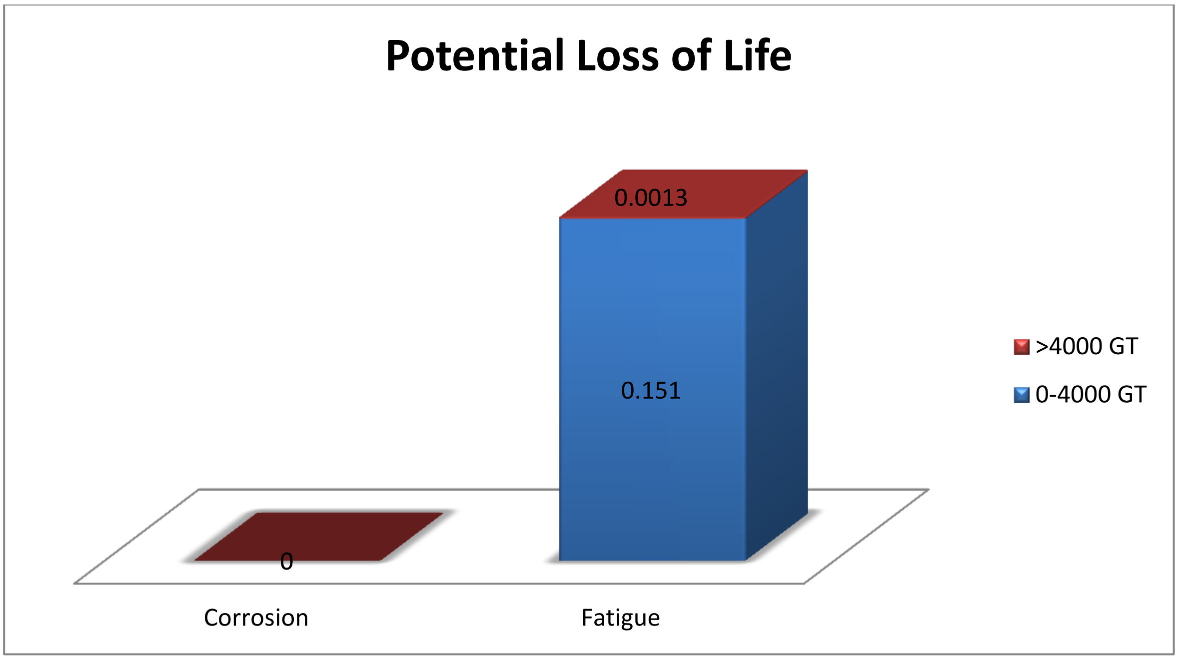


Figure 6.1: Rates of PLL's cumulative risk for each specified category

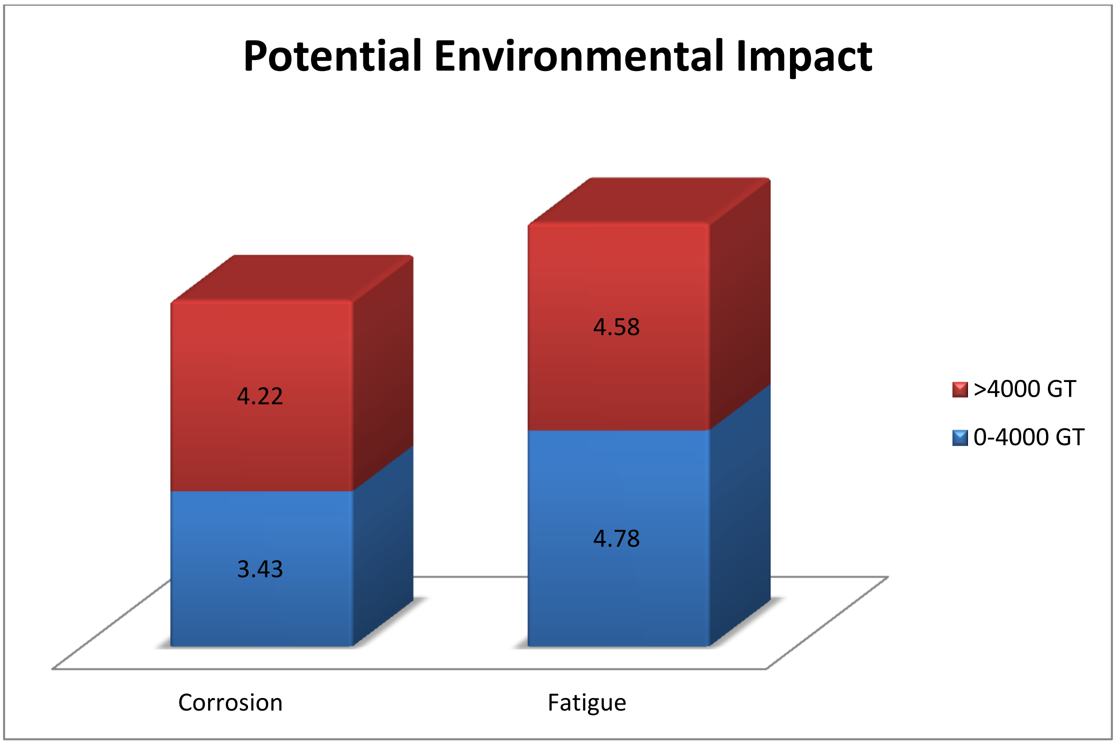


Figure 6.2: Rates of PEI's cumulative risk for each specified category

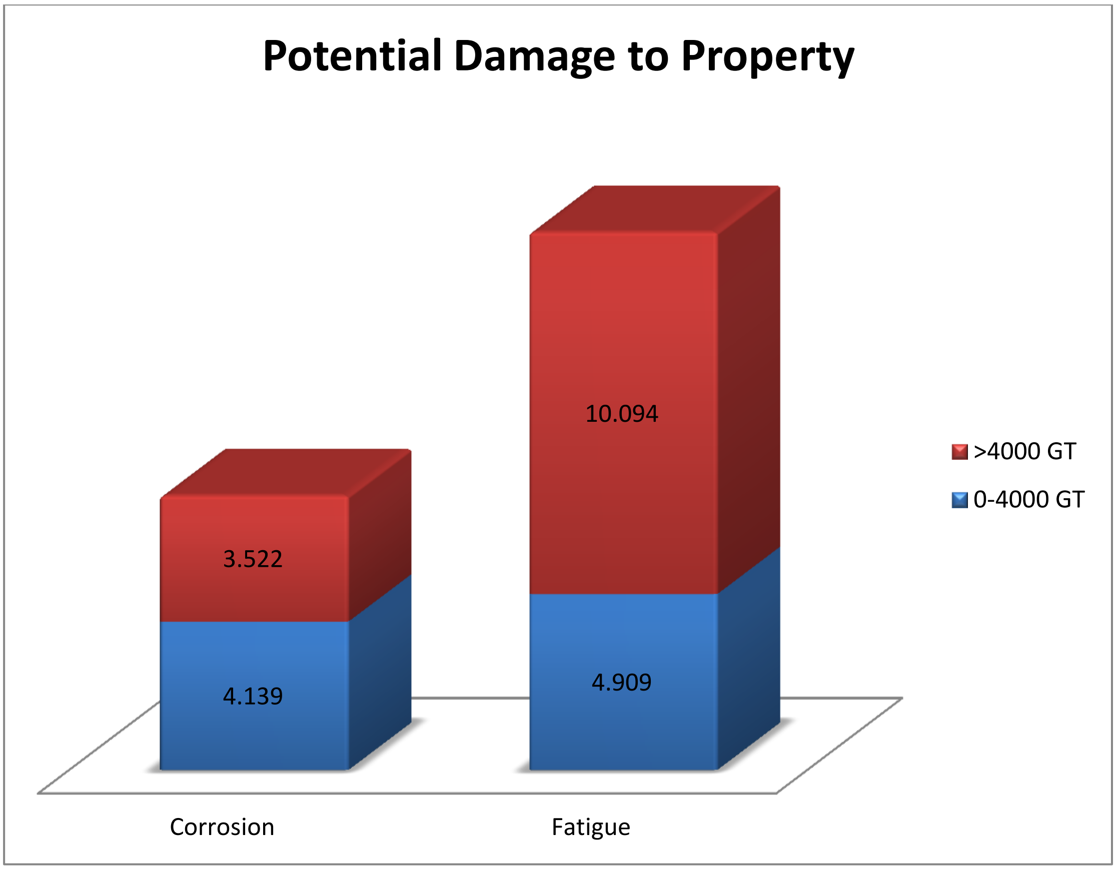


Figure 6.3: Rates of PDP's cumulative risk for each specified category

Failures due to Corrosion

It is known that corrosion plays a significant role to the structural failure of a ship and it could be very constructive for future ships' buildings to have recognized corrosion causes and consequences. Following this, a table and a graph in relation to the average cost for the asset and the average pollution are presented below. It must be noticed that the factor of fatalities do not make sense to be analysed in current failures as no fatality was observed during the investigation.

By Table 6.1 and Figure 6.4 crucial results for the environmental impact can be issued with regard to the different consequences that predominate in each size category. As it can be noticed, even though the probability of a "Total Loss" and the oil spill that derives by it is more essential in small class than the large class, the pollution's probability is bigger in large class.

	4,000GT and below		4,000GT and above	
Degree of Severity	*Probability (%)*	*Cumulative Risk of Pollution per state (tonnes)*	*Probability (%)*	*Cumulative Risk of Pollution per state (tonnes)*
Total Loss	20.5	3.13	6.3	4.02
Refloat	2.56		3.1	
Significant	36.52	0.3	37.6	0.2
Minor	37.86		53	
Scrap	2.56			
Total	100	***3.43***	100	***4.22***

Table 6.1: Relative probabilities and amounts of pollution for environmental impact consequences taking into account the Degree of Severity

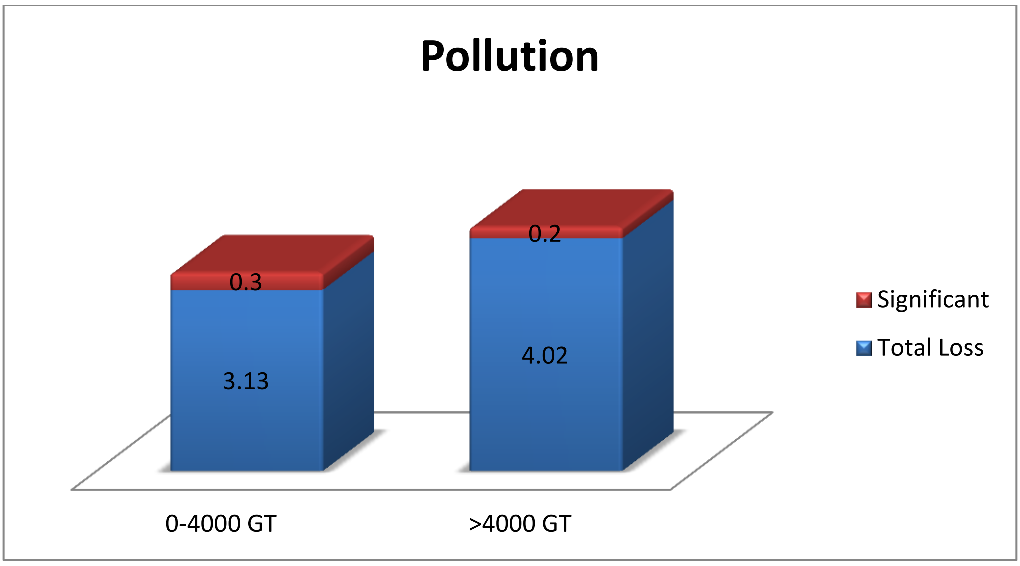


Figure 6.4: Cumulative Risk of Pollution for each category of RoPax

Furthermore, it has to be shown the average cost of each fleet (Table 6.2) so as everyone to understand the damage that a ship company may be suffered. Comparison of two fleets indicates that the average cost for 4000GT and above is less than the fleet of 0-4000 GT and below. This is reasonable as “Total Loss” was appeared in more ships for small category.

	0-4,000GT and below		4,000GT and above	
Degree of Severity	*Probability (%)*	*PDP (million $) per State*	*Probability (%)*	*PDP (million $) per State*
Total Loss	20.50	3.783	6.30	3.150
Refloat	2.56	0.158	3.10	0.372
Significant	36.52		37.60	
Minor	37.86		53.00	
Scrap	2.56	0.198		
Total	100	***4.139***	100	***3.522***

Table 6.2: Relative property’s cost for each fleet with respect to Degree of Severity

Failures due to Fatigue

Analysis of these kinds of incidents occurred in relation to the fatalities that happened, the damage to property and the amounts of the spread oil. Derived results contribute to perceive the significance of failures due to fatigue and they are listed collectively below.

Investigating data showed that for specific failures are observed fatalities and injuries. So, in Table 6.3 their rates are mentioned:

	4,000GT and below		**4,000GT and above**	
Degree of Severity	*Probability (%)*	*Cumulative Risk of Losses of Life*	*Probability (%)*	*Cumulative Risk of Losses of Life*
Total Loss	24.67	0.150	7.70	
Refloat			3.84	
Significant	41.46	0.001	48.08	0.0013
Minor	31.27		36.53	
Scrap	2.60		3.85	
Total	100	***0.151***	100	***0.0013***

Table 6.3: Amount of potential losses of Life (PLL) with respect to degree of severity

The research continued with taking into consideration the amount of oil spills and the distribution of pollution in relation to each degree of severity. Table 6.4 and Figure 6.5 represent the results of this research:

	4,000GT and below		**4,000GT and above**	
Degree of Severity	*Probability (%)*	*Cumulative Risk of Pollution per state (tonnes)*	*Probabilit y (%)*	*Cumulative Risk of Pollution per state (tonnes)*
Total Loss	24.67	4.78	7.70	4.44
Refloat			3.84	
Significant	41.46		48.08	0.14
Minor	31.27		36.53	
Scrap	2.60		3.85	
Total	100	***4.78***	100	***4.58***

Table 6.4: Relative probabilities and quantities of oil spills for environmental impact consequences taking into account the Degree of Severity

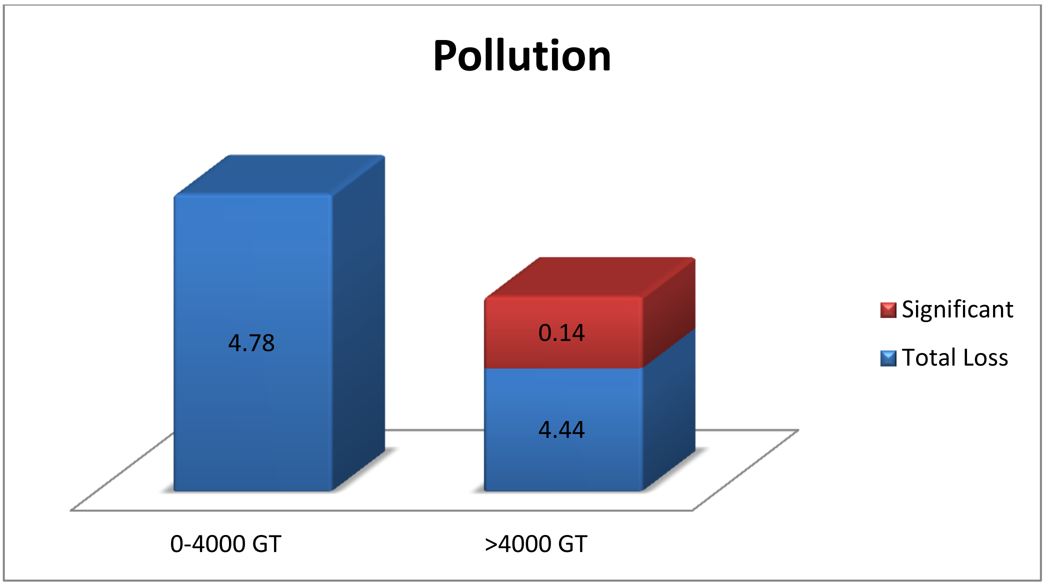


Figure 6.5: Quantity of the potential environmental impact in tons for each ship's category

Finally, a correlation between the two categories of RoPax sizes occurred according to the damage to property and average costs as also and costs for each ship are estimated in relation to the degree of Severity (Table 6.5).

	0-4,000GT and below		**4,000GT and above**	
Degree of Severity	*Probability (%)*	*PDP (million $) per State*	*Probability (%)*	*PDP (million $) per State*
Total Loss	24.67	4.755	7.70	6.550
Refloat			3.84	0.646
Significant	41.46		48.08	
Minor	31.27		36.53	
Scrap	2.60	0.154	3.85	2.898
Total	100	***4.909***	100	***10.094***

Table 6.5: Relative potential cost for every specified category of fatigue failure in million euros for each Degree of Severity

7. Advanced Risk Analysis of Non Accidental Failures

After a lot of consideration, the conclusion that the outcomes, which were resulted by Event Tree Analysis, must be examined with regard to their accuracy emerged. In other words, it was attempted to find distributions with respect to the costs, the pollution and their cumulative risks so as to ensure that Risk Analysis results are representative for the fleet of the database.

The determination of the distributions based on data which was taken by the concerned database and on the method of Monte Carlo simulation.

Monte Carlo simulation is a method which took its name by the city of Monte Carlo due to the fact that specific city is characterized as the capital of gambling. Its name is subjected to the uncertainties that a problem may have and the process that is followed to reach conclusions about a problem. The simulation process includes generation of chance variables and exhibition of their random behavior. Moreover, Monte Carlo is a vital statistical tool with utilities in both engineering and non-engineering field that is usually used for optimization, numerical integration and drawing conclusion from probability distributions. It is widely known that Monte Carlo Simulation can solve any problem which has a probabilistic interpretation and estimate expected values via the probability density functions (A. Douchet, 2001)

Furthermore, because of the capability of Monte Carlo simulation to create an oversupply of potential outcomes for uncertain inputs with the simultaneous definition of their boundaries, its significance to the quantification of the risk in various projects and studies is great.

7.1 Monte Carlo Simulation Model

At this point of current thesis, the outcomes of the Monte Carlo Simulation Model, which developed, are going to be presented. It must be remarked that this Model was implemented with respect to the previous Risk Analysis which occurred for the four predefined categories of RoPax ships. Furthermore, two more general classes were used for the performance of specific Analysis so as the results of current research to become more obvious.

So, the Dynamic Risk Model was developed for the six categories of RoPax ships that are listed below:

- RoPax ships of *4,000 GRT and below with the presence of cracks, dents and fractures (Small class with fatigue failure).*
- RoPax ships of *4,000 GRT and below with appearance of corrosion (Small class with corrosion).*
- RoPax ships of *4,000 GRT and above with the presence of cracks, dents and fractures (Large class with fatigue failure).*

- RoPax ships of *4,000 GRT and above with appearance of corrosion (Large class with corrosion).*
- RoPax ships of *4,000 GRT and below with the presence of Non Accidental Structural Failures (Small Class of Ships).*
- RoPax ships of *4,000 GRT and above with the presence of Non Accidental Structural Failures (Large Class of Ships).*

As a result, a wide variety of graphs and distributions were developed in relation to the basic design characteristics of ships that was taken into consideration such as Gross Tonnage (GT), Lightship (LS) and GT*Speed. Moreover, diagrams that are subjected to the Environmental Impact and Damage to Property were resulted not only as an entity for each specified class but with respect to the Degree of Severity of each casualty too.

The whole research based on 4,203 vessels which their data either combined with the aim of drawing the expected results or used as they were wherever ships' characteristics were obvious.

An indicative example of drawing the expected results was the Lightship, as its value was unknown for a wide percentage of RoPax ships due to the underreporting of the IHS database. But because of the adequate information that had been given for the Breadth, Length, Draught and Deadweight for each ship, it was feasible to estimate the Lightship for ships that their value was given by the database as zero. It is known that (Papanikolaou, 2009):

Displacement is $\Delta = c_B * B * L * T * \rho_{SW}$,

where: B= *Breadth of each ship (in meters)*

L= *Length of each ship(in meters)*

T=*Draft of each ship(in meters)*

ρ_{sw}= *1.025ton/m*^{3} *for salt water*

c_B= *Block coefficient*

While Lightship is $LS=\Delta-DWT$, where *DWT=Deadweight of each ship*

As a consequence, values of Lightships were assessed for all ships of database fleet with the only assumption that c_B= 0.6, a typical value of the block coefficient for RoPax ships as its proposal values in case of missing data are 0.55-0.65 (Pianc,2002).

Therefore, having acquired knowledge about Lightship, distributions of the LS for the Small and Large class of GT were formed. Two other distributions with regard to the Gross Tonnage of the given data had already been found for these classes too.

So, cost distributions for the three Degrees of Severity (Total Loss, Scrap, and Refloat) had been illustrated and limits of minimum and maximum values of the costs were set. It is necessary to be written that for the assessment of the cost for a Total Loss, DNV-GL's formula was used like in the Risk analysis too and its equation was: $Cost_{Total\ Loss} = 76{,}976 * GT^{0.7663}$

Refloat's costs were the 25% of Total Loss costs and Scrap's cost were calculated as the difference between the cost that the ship would have in case of its loss with the benefit from the scrapping.

In addition, pollution distributions in case of the loss of the ship and for significant incidents were found. For achieving this, fuel capacities had to be estimated firstly with another formula that was proposed by DNV-GL and its equation was:

$$Tank\ Capacity = 0.1665 * (GT * Speed)^{0.6939}$$

It has to be remarked that GT*Speed distributions had already been found by the data which were given by IHS database. As a result, quantities of oil that could be released in case of the loss of a ship were assessed as the percentage of 30% of the fuel capacities, while the percentage of 2% was taken for the pollution that would have been spread in case of significant incidents.

Furthermore, risk contribution distributions for the damage to property and environmental impact were estimated. Moreover, their outcomes compared with the results that had emerged by previous Risk Analysis (Chapter 6) as the aim was to find the relation between the consequences that were derived by the accident reports for NASF and the theoretical values which estimated via the current model that was taken into consideration the whole fleet. It is vital to be mentioned that probabilities for calculating cumulative risks and consequently finding their distribution had been presumed equal to those that had represented the existent accidents.

Finally, it is necessary to be mentioned that the distributions of the concerned factors occurred by two ways:

1. *Analysing data of the database.*
2. *Combining Monte Carlo Simulation with data analysis of the database.*

7.2 Results of Monte Carlo Simulation Model

By using @Risk software of Palisade, it was feasible to find the most suitable distributions for a variety of data and perform Monte Carlo Simulation wherever was necessary.

7.2.1 Preliminary Analysis

Initially, it was absolutely essential for the progress of current analysis to find the distribution of Gross Tonnage (GT), the distribution of Lightship (LS) and the distribution of the GT*Speed product for each class of ships with respect to GT (Small and Large Class).

For that reason, two graphs were formed with respect to Gross Tonnage, the first one for the Small Class (Figure 7.1) and the second one for the Large Class (Figure 7.2).

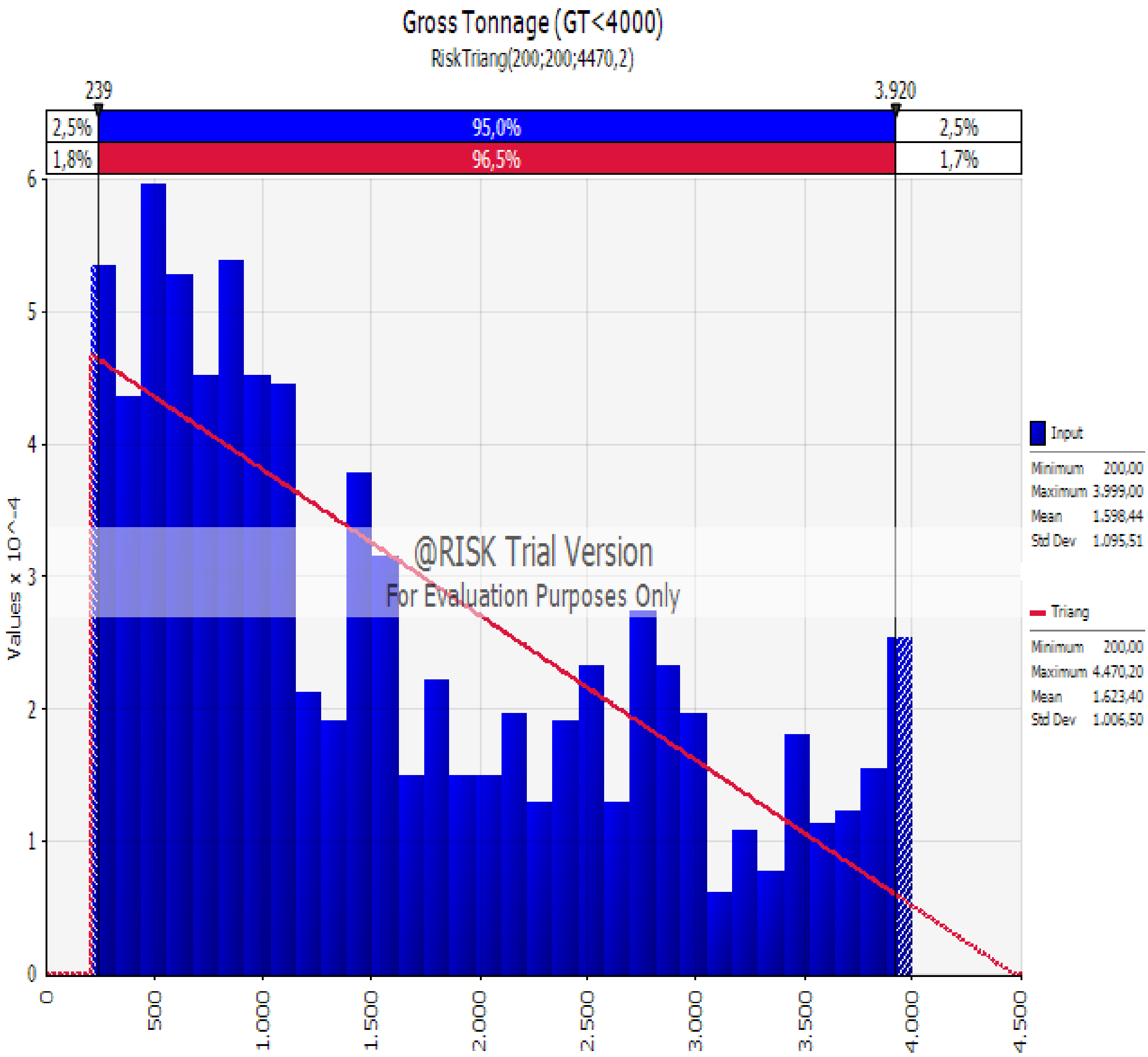


Figure 7.1: Graph with respect to GT distribution for Ships with 4,000 GT and below

As it can be easily seen by Figure 7.1, the minimum value of RoPax ships that were taken into account was 200GT and the maximum was 3,999 GT. Also, it must be explained further that current Figure contains the histogram which is shown with the blue color and the best fitted distribution that is related with the data illustrated with red color. As a consequence, the outcome that a Triangular Distribution is best for this class of GT is conspicuous. The peak value of the triangular distribution was for 200GT.

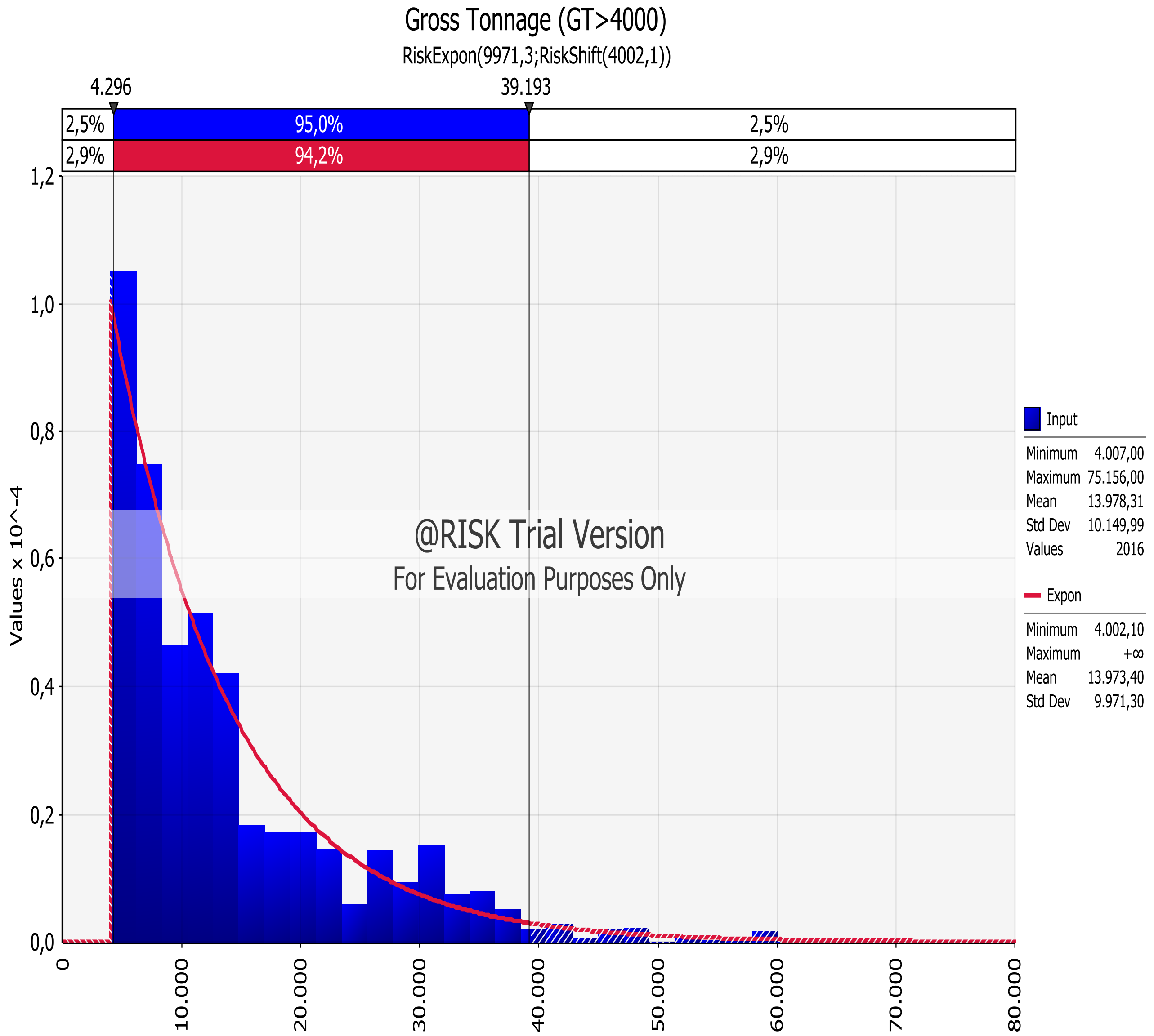


Figure 7.2: Graph that shown Gross Tonnage Distribution for RoPax ships with 4,000 GT and above

Figure 7.2 shows how Ships' Gross Tonnage in the Large class of RoPax ships disturbed and leads us to the effect that GT in specific class follows an Exponential Distribution. The concerned fleet has as a minimum of GT, the value of 4,007 GT and as a maximum, the value of 75,156 GT. The mean value of the large class is 13,973.4GT and represents the 1/λ of the distribution where λ is the parameter of the specific exponential distribution.

In the sequel, two diagrams with respect to Lightship (LS) were conducted with the predifined method so as to have a general aspect about the distribution of the Lightship for the Small and Large class of RoPax vessels.

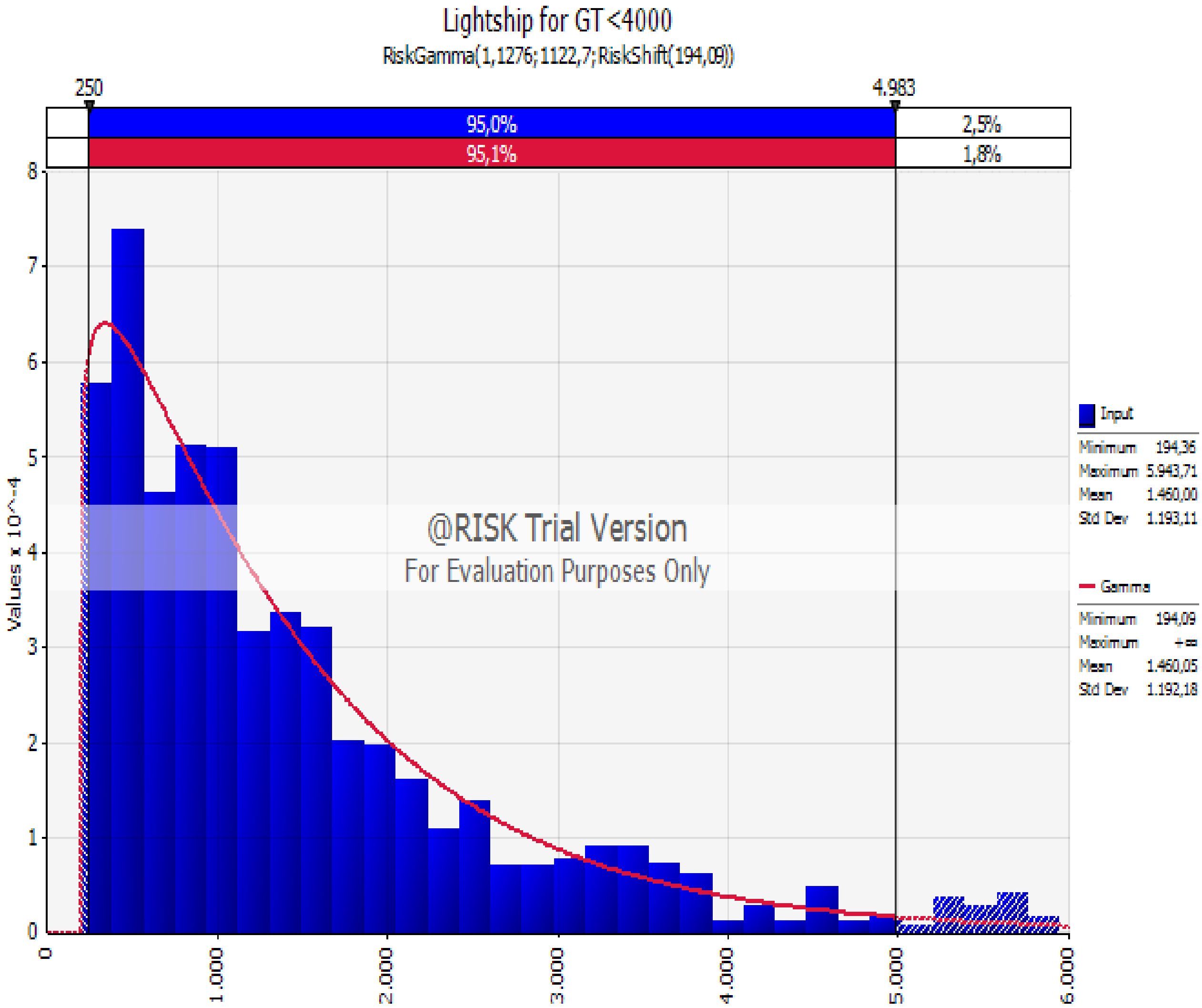


Figure 7.3: Features of Lightship distribution for RoPax Ships<4,000GT

In Figure 7.3, LS values for the Small Class of RoPax vessels seems to vary a lot and be compatible with Gamma Distribution whereas the Large Class of considered ships is subjected to a Log-Normal Distribution as far as LS is concerned (Figure 7.4) with μ=10,970.29 and σ=7,570.6.

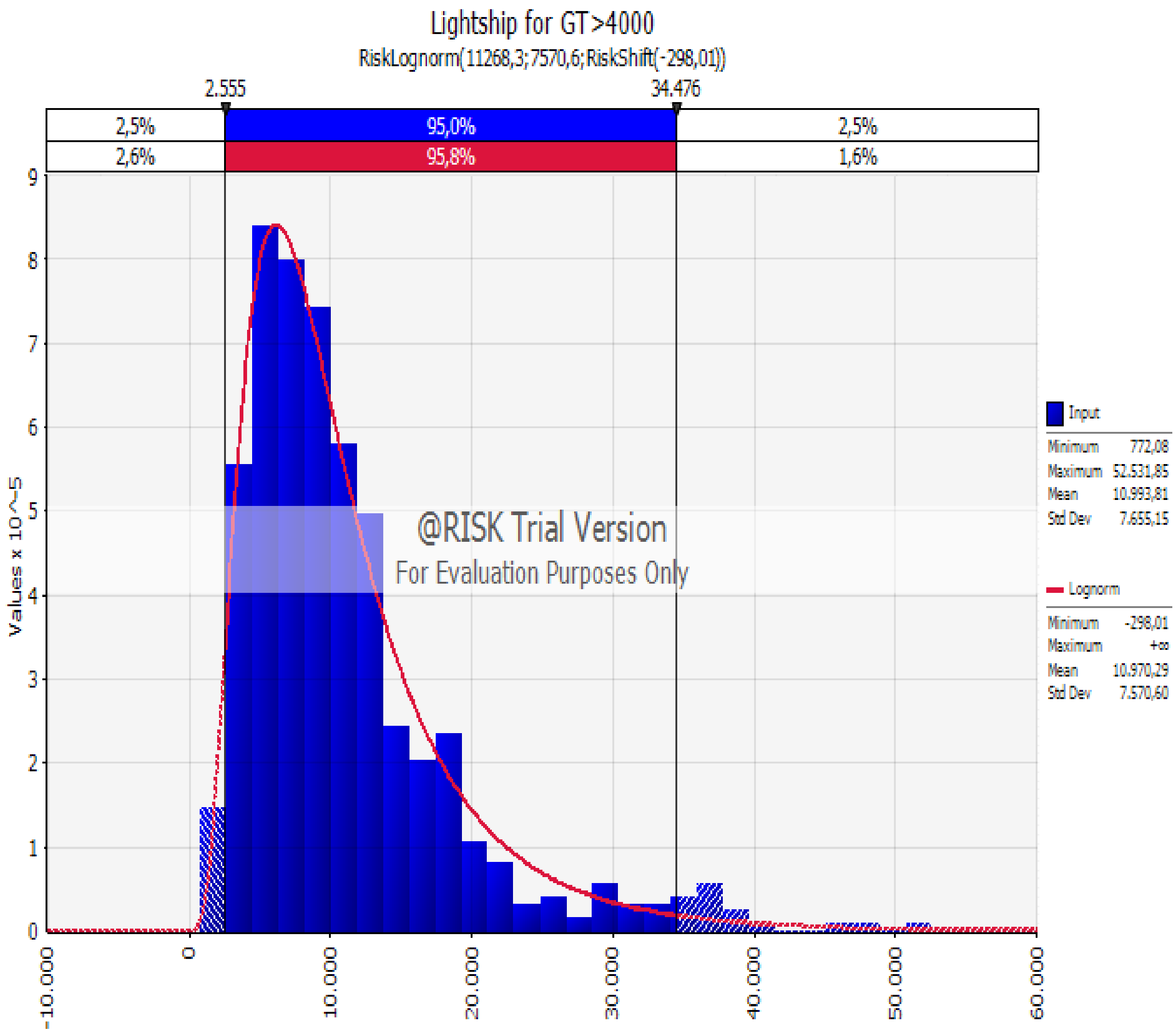


Figure 7.4: Features of LS for Ships with 4,000 GT and above

Finally, due to the fact that formula of pollution contained the product of GT*Speed, it was necessary to estimate two distributions for the two classes of the RoPax ships, Small class (Figure 7.5) and Large class (7.6).

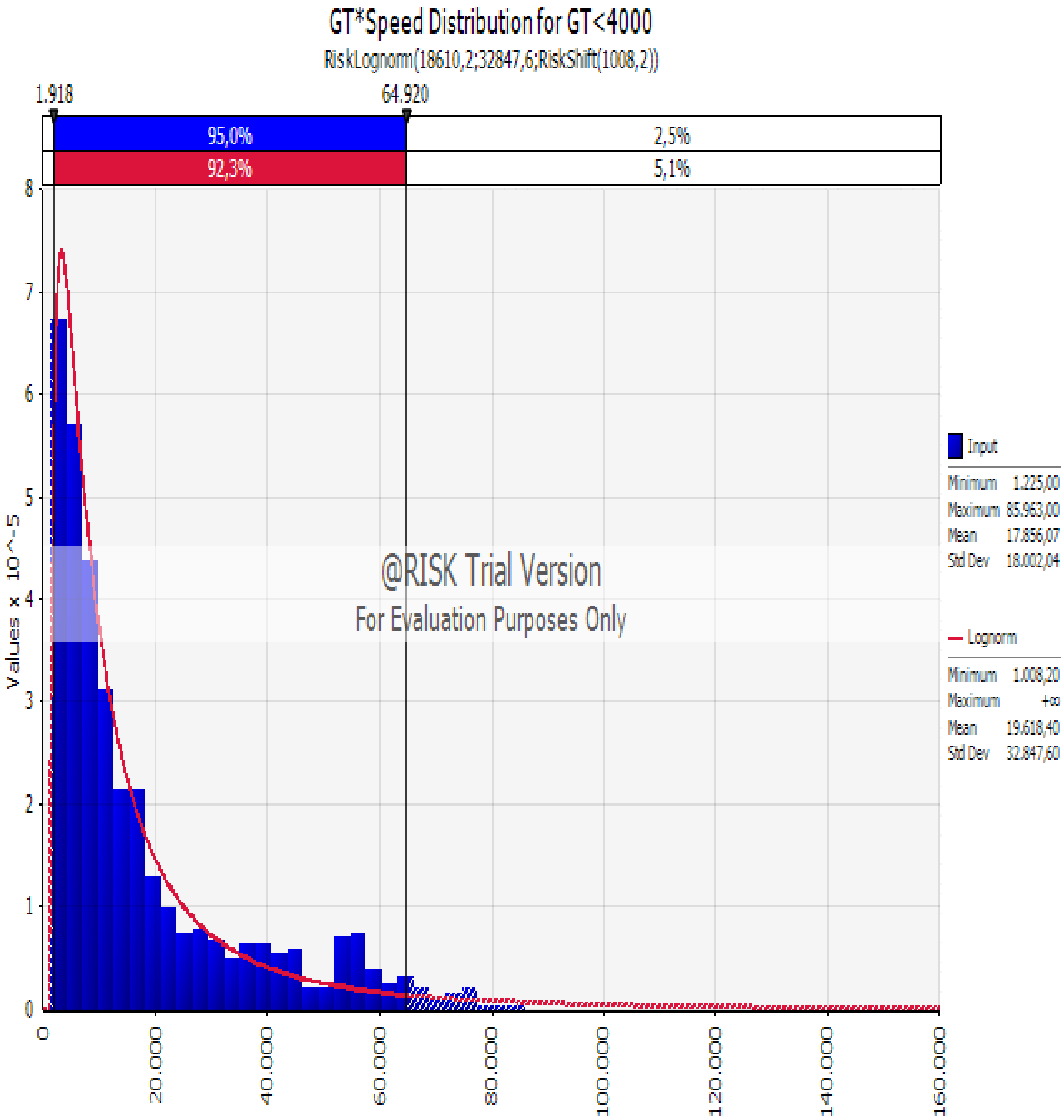


Figure 7.5: Distribution of GT*Speed for RoPax Ships< 4,000GT

Both distributions follow the Log-Normal distribution. For the Small class (Figure 7.5), distributions parameters are μ= 19,618.4 and σ=32,487.6, whereas for the Large Class distribution's parameters are μ=220,890.9 and σ=180,950.5 (Figure 7.6).

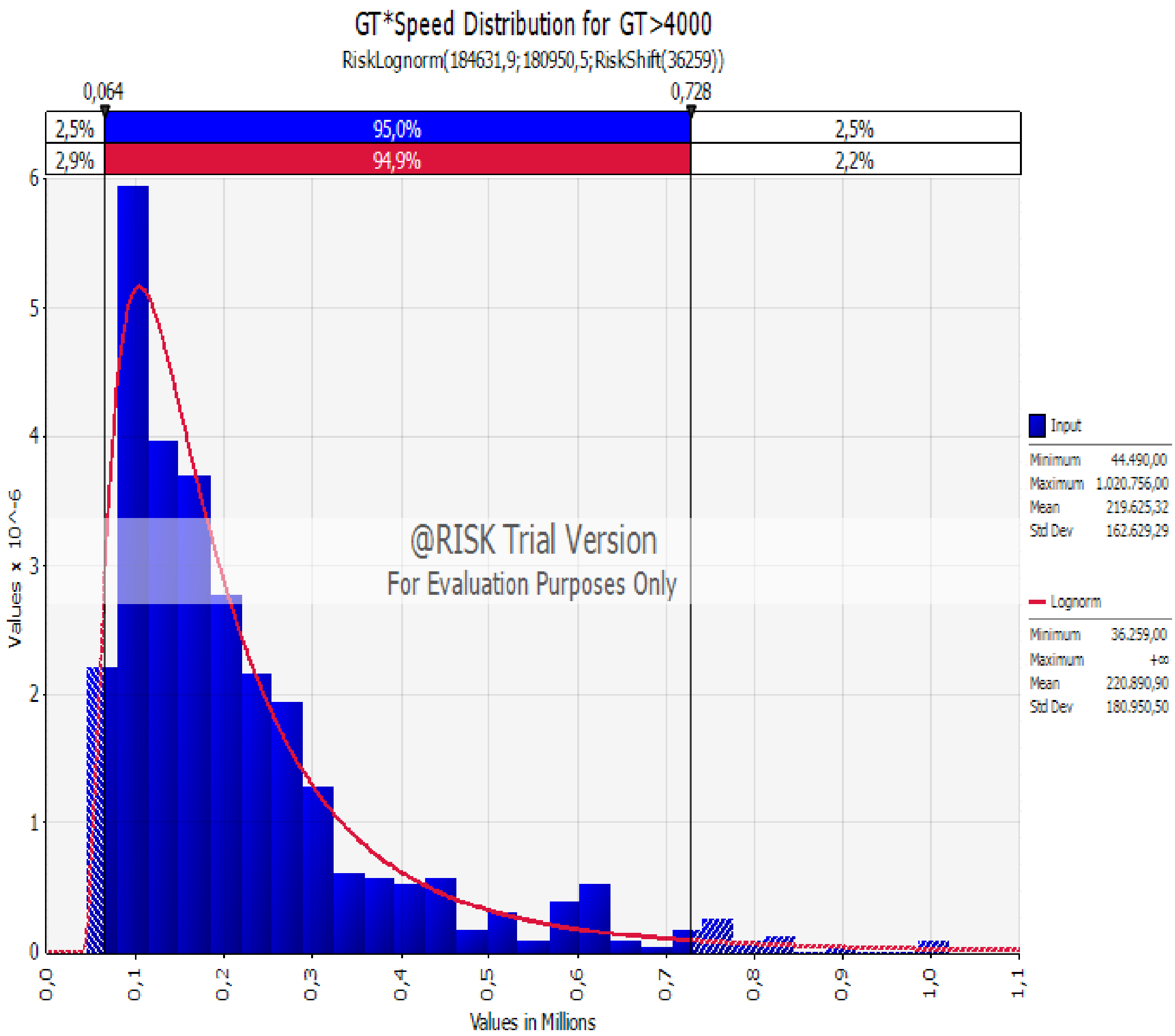


Figure 7.6: Distribution of GT*Speed for RoPax Ships>4,000GT

After the preliminary analysis it was feasible to combine these estimated distributions and use them for finding some other distributions in relation to the Degree of Severity, ships classes and the consequence of each incident.

7.2.2 Main Analysis with regard to Damage to Property

In this section of specific thesis, an effort of evaluating the costs and potential costs of ship owners in the cases of a Total Loss, Refloat and Scrap is attempted with the assistance of Monte Carlo Simulation.

Firstly, it must be mentioned that for the six predefined categories of current analysis, ownership costs differ only with regard to the two classes of GT (Small and Large) and casualties' Degree of Severity. So, it is meaningless to say that the type of failure (corrosion or fatigue) does not play a role to the magnitude of the cost.

RoPax Ships with 4000 GT and below (Small class)

The distribution of the cost that the asset has when a RoPax vessel is lost after an accident is obvious from Figure 7.7. The minimum cost of an owner it seems to be about 4.463 million euros while maximum expenses can reach 44.241 million euros for bigger vessels of current class. As it has already mentioned, mean value represents the expected value of ships that might be lost and it is equal to 19.740 million euros.

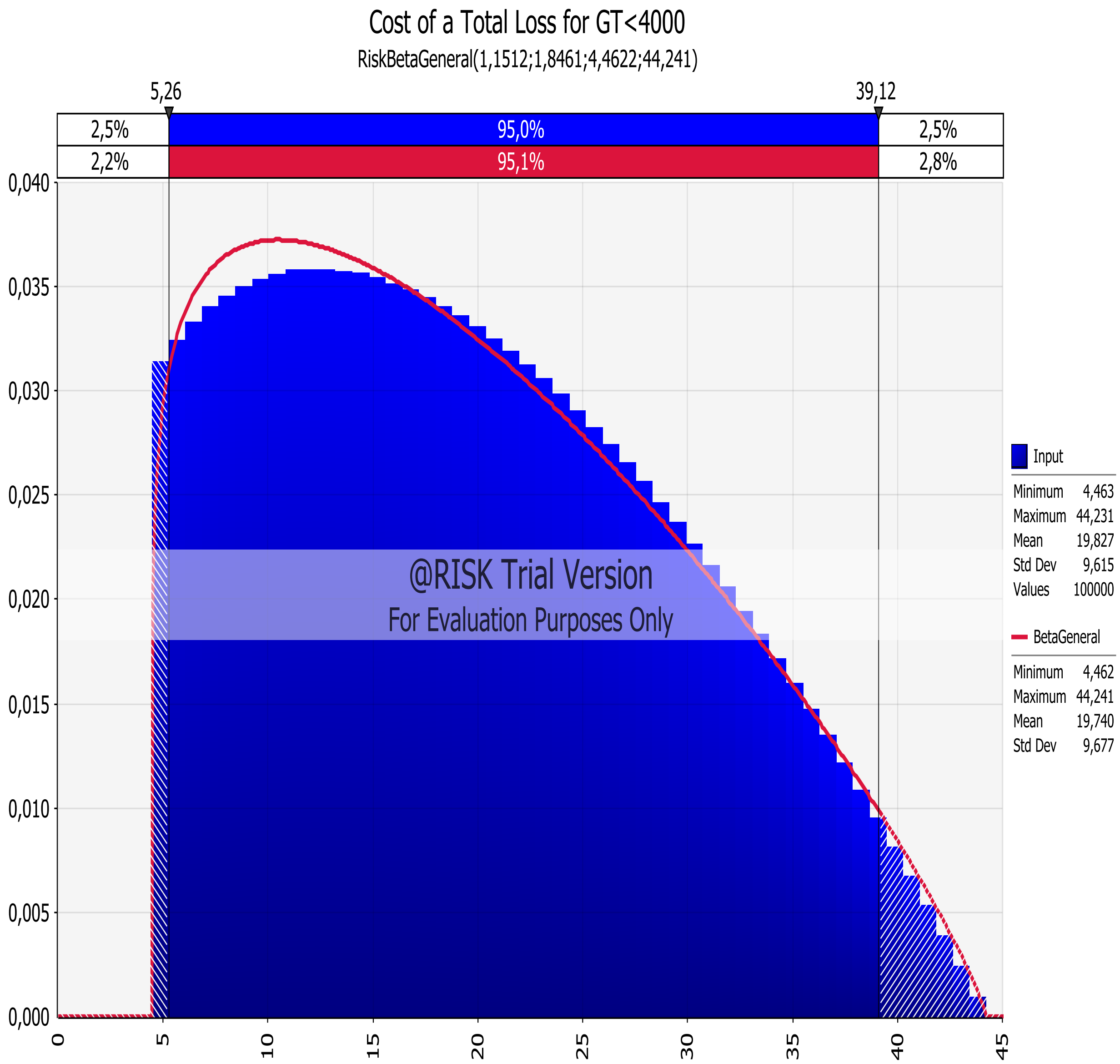


Figure 7.7: Graph of the cost when a Ship<4,000 GT is lost in million euros

It must be remarked that filters for GT's distribution were put in the software because the form of the triangular distribution that specific class of ships follows, could have taken values that correspond to Gross Tonnage bigger than 4,000. Another outcome that derives from the Figure 7.7 is the type of distribution that fits the costs for Total Loss. It goes without saying that Beta General is the best fit for all the costs which have taken into account from the software with the performance of Monte Carlo Simulation.

Furthermore, an illustration of the damage that property suffered when a ship Refloated is shown in Figure 7.8. Refloat distribution was formed too, as the 25% of a Total Loss cost has already predefined that is equal to Refloat cost. So, values of Total Loss costs multiplied with specific percentage and a new distribution was fitted to current data.

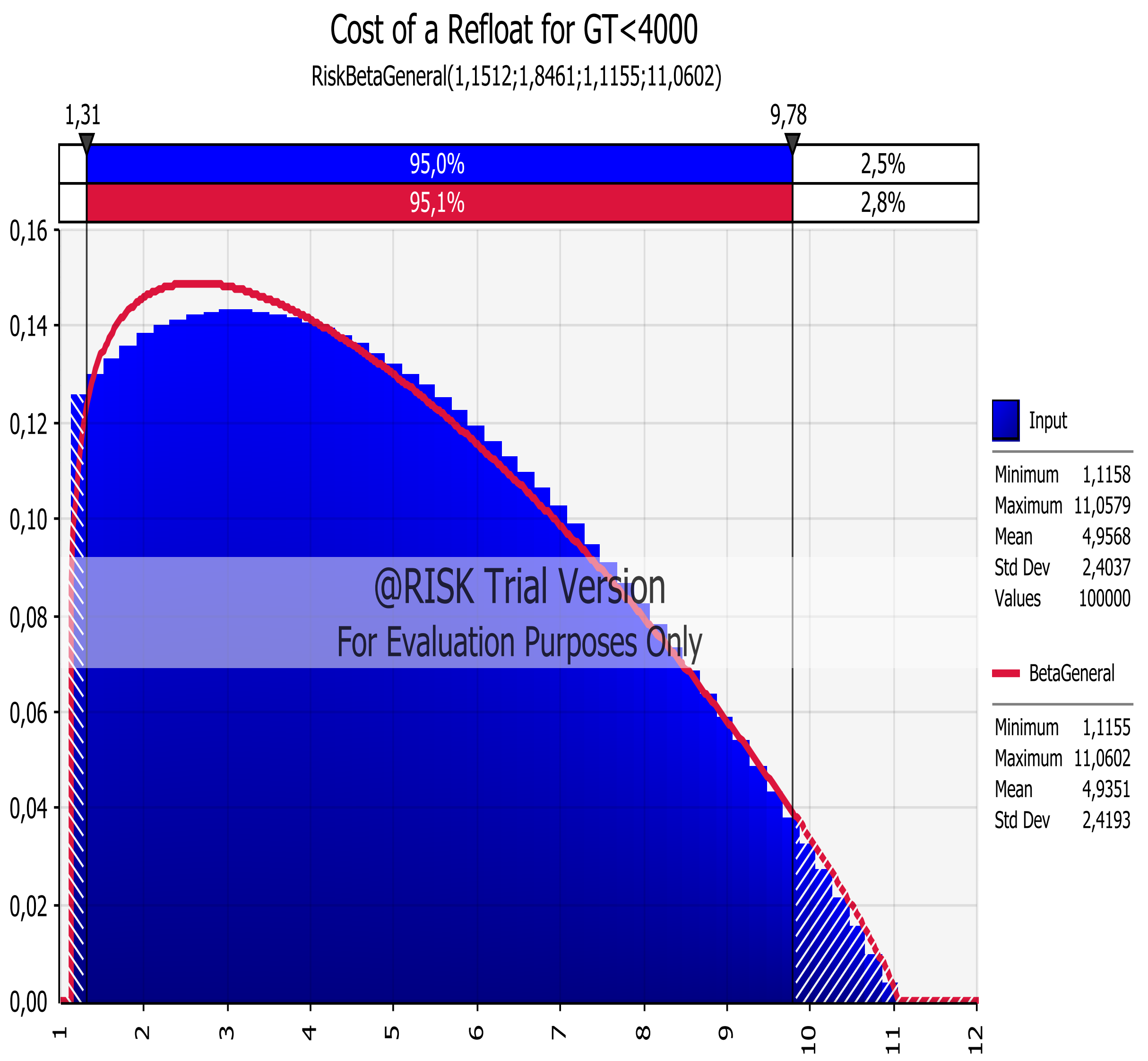


Figure 7.8: Features of cost of a Refloat for Vessels <4,000 GT in million euros

The highest cost for a shipping company is about 11.060 million euros and the lowest is 1.155 million euros. It is also vital to be mentioned that Beta General is the distribution that this kind of costs belongs to and its shape parameters corresponds for α=1.512 and β=1.8461.

In addition, a diagram for the expenditures of an owner when his/her ship goes for scrap after an incident is displayed (Figure 7.9). A significant issue that must be pointed out here, it is the values that this graph had taken as an input for its formation which seems to contain 99,140 data. This happens because of the implemented restrictions with regard to the upper and lowest costs for this category costs. So, although simulation occurred for 100,000 values, a small amount of them was excluded by the program.

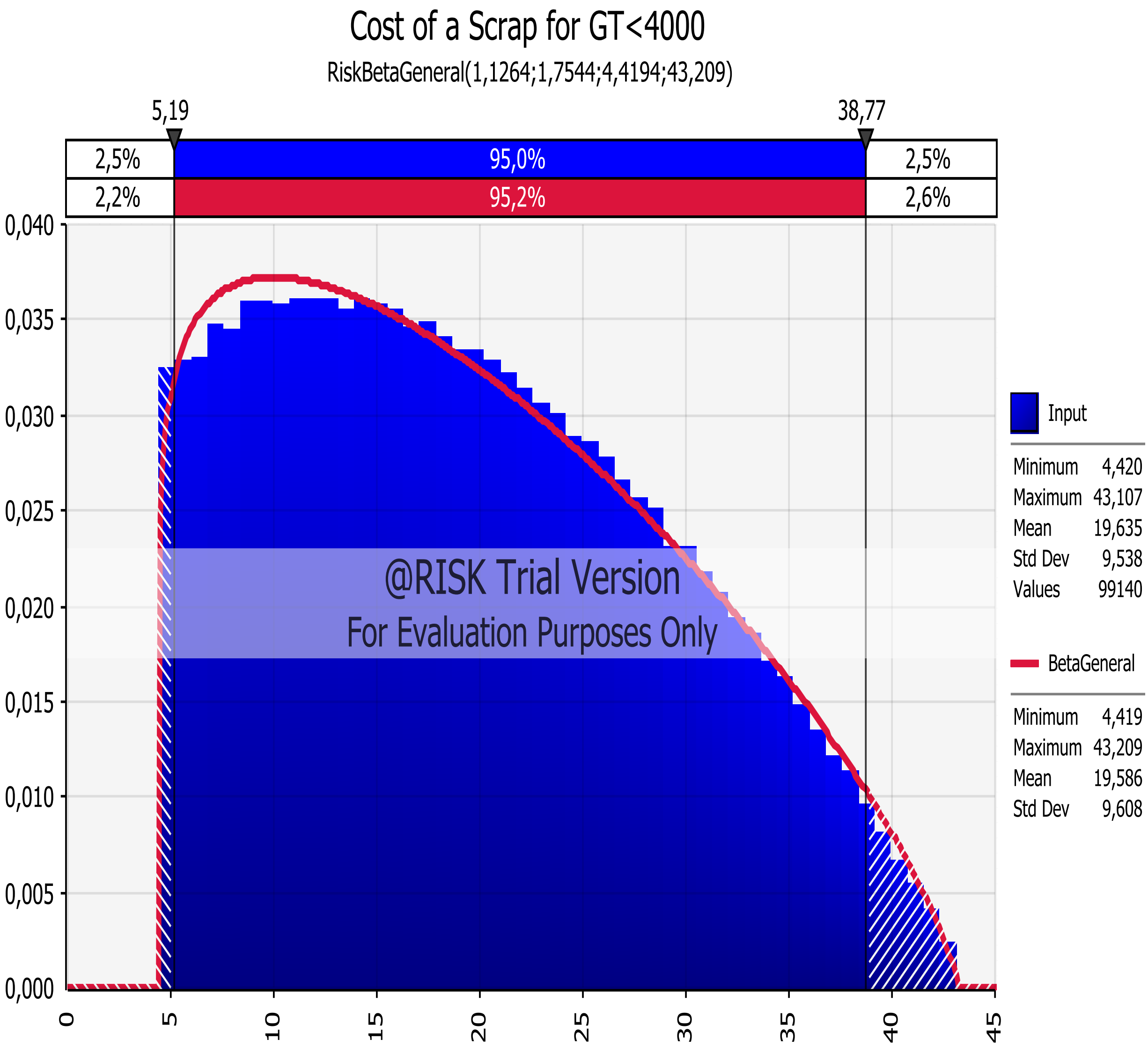


Figure 7.9: Diagram for the cost of a Scrap in specific class of RoPax ships in million euros

The tendency of the damage that shipping companies suffer to follow a Beta General Distribution is verified in the occasion of a Scrap too.

With the assistance of the above diagrams and the outputs of them, it was feasible to appraise the Potential Damage to Property (PDP) for all RoPax ships under 4,000GT regardless of whether they had involved in an accident or not. So, it became possible to make a comparison between the outcomes of the Event Trees that were developed during the Risk Analysis and the outputs of Monte Carlo Simulation.

After a critical review, an initial approach of the cumulative risk with regards to the cost, it was implemented so as to establish the potential Damage to Property for Non Accidental Structural Failures (NASF) for RoPax vessels with 4,000 GT and below.

At first, the possibility of a total loss of a ship in specific category was estimated with the aid of the investigating reports for NASF. This probability was calculated approximately 22.62% for the small class of ships and by using the outputs of Figure 7.7, the distribution for the cumulative risk of a Total Loss with respect to the cost was found (Figure 7.10).

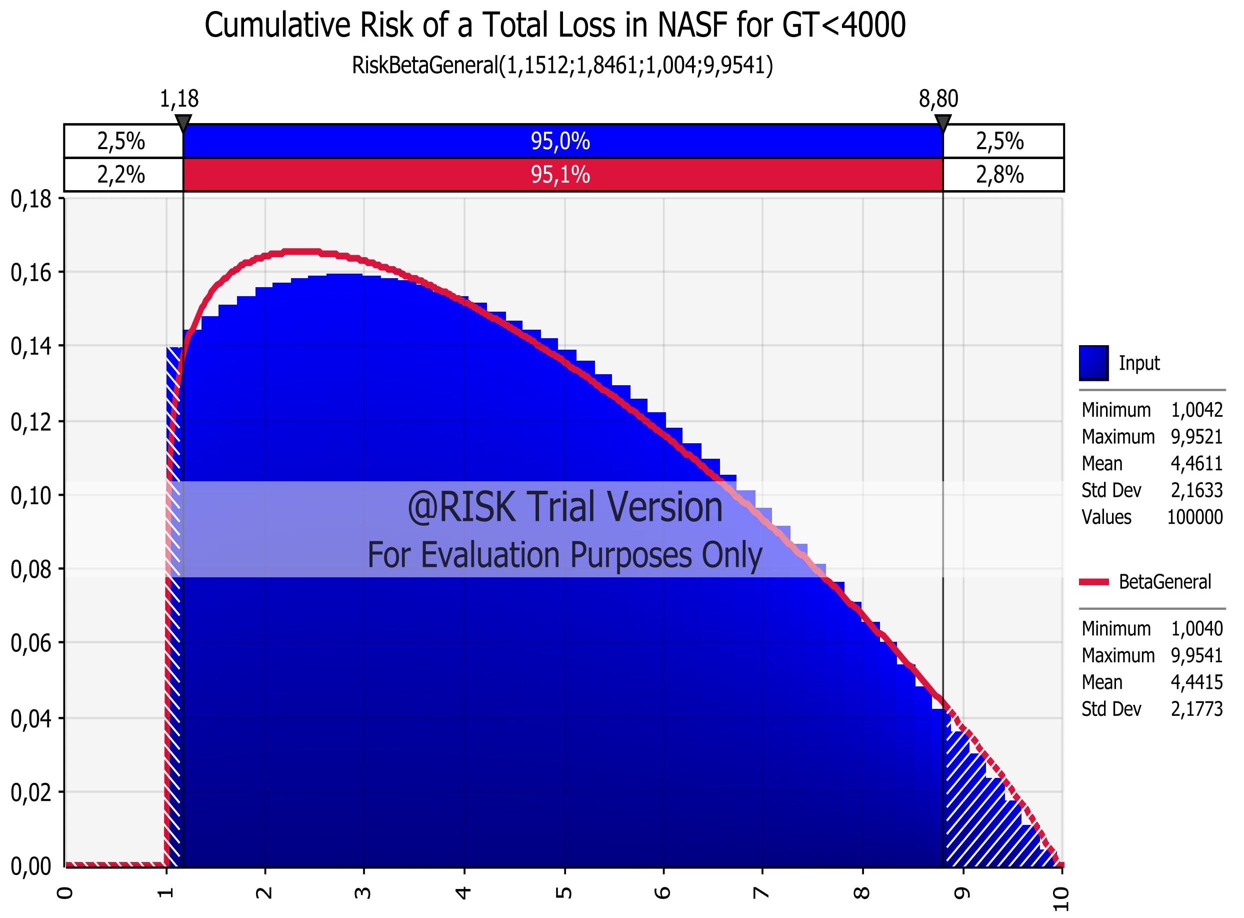


Figure 7.10: Distribution of PDP for a Total Loss of a RoPax< 4,000GT with NASF

A crucial outcome deriving from the above diagram (Figure 7.10) is that the expected value (mean) of the Beta General Distribution which characterizes the PDP is about 4.461. A detailed research on the existent data of NASF casualties gave the outcome that the relevant cumulative risk was about 4.438. It is obvious that these two values are very close and as a matter of fact the Event Tree analysis was indicative for the tendency of specific risk contributor.

Moreover, the probability of 0.86% assessed for the occurrence of a Refloat in NASF via SEAWEB's data. So, it was easy to figure the distribution for the cost's cumulative risk of a Refloat (Figure 7.11).

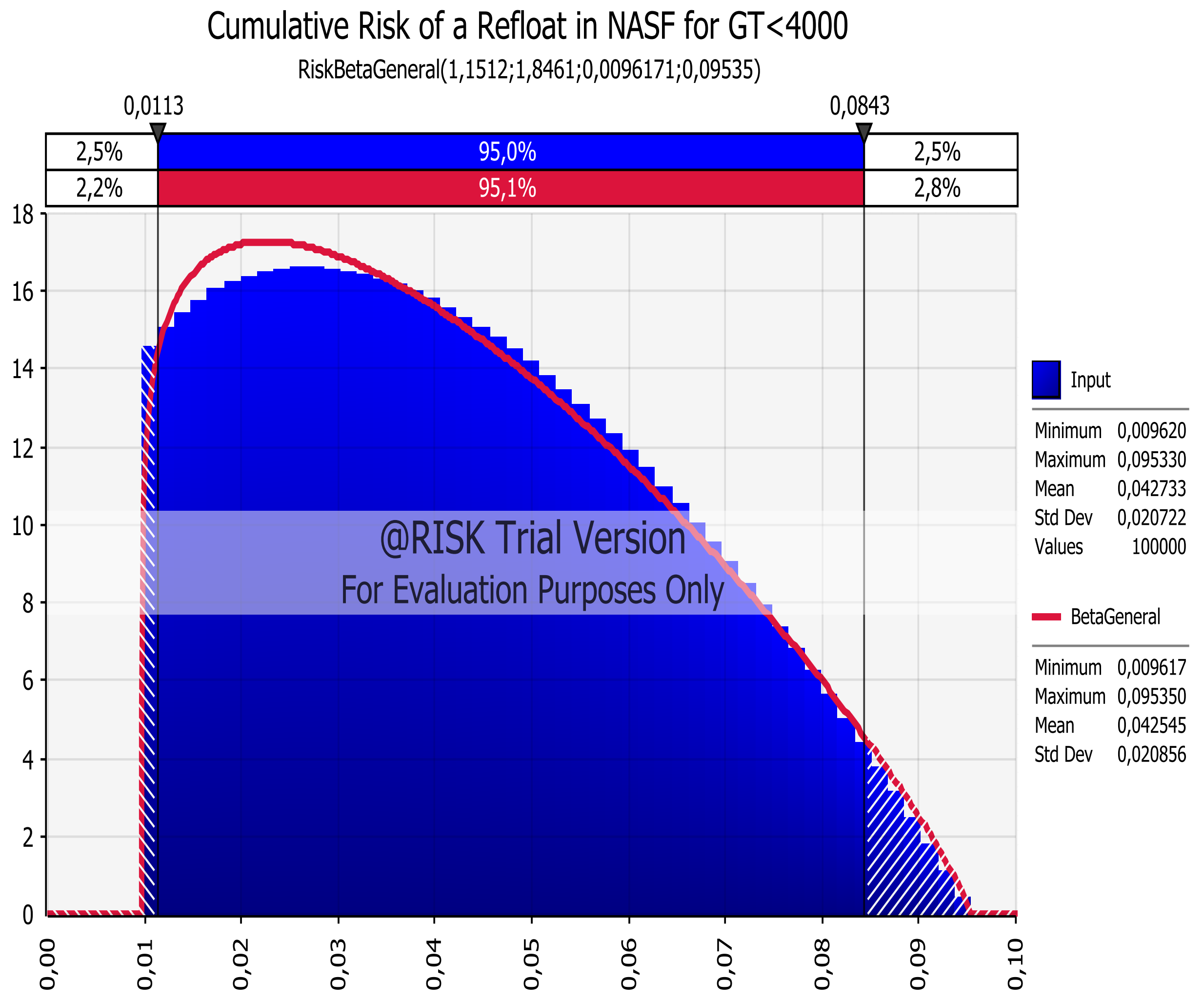


Figure 7.11: Distribution of PDP for a Refloat of a RoPax< 4,000GT with NASF

It is clear that the expected value of the cumulative risk with respect to the cost when a vessel refloated is approximately 0.043, while its boundaries are between 0.010 and 0.095 (Figure 7.11). The value of cumulative risk that assessed from the concerned data was 0.054. This discrepancy is justified due to the fact that the one vessel which refloated in current class has 1,887 GT while the mean value of GT for Ships<4,000GT is about 1,598GT (Figure 7.1). So, it is an undisputed fact that the sample of 100,000 data that are used by Monte Carlo Simulation is more reliable than the existent consequences of the one accident.

The last factor which interferes to the creation of the aggregated Potential Damage to Property is PDP of Scrap. The probability of the Scrap in current class is 2.59% and if it is considered that the distribution of the Lightship had already been known, the distribution of specific PDP was evaluated (Figure 7.12).

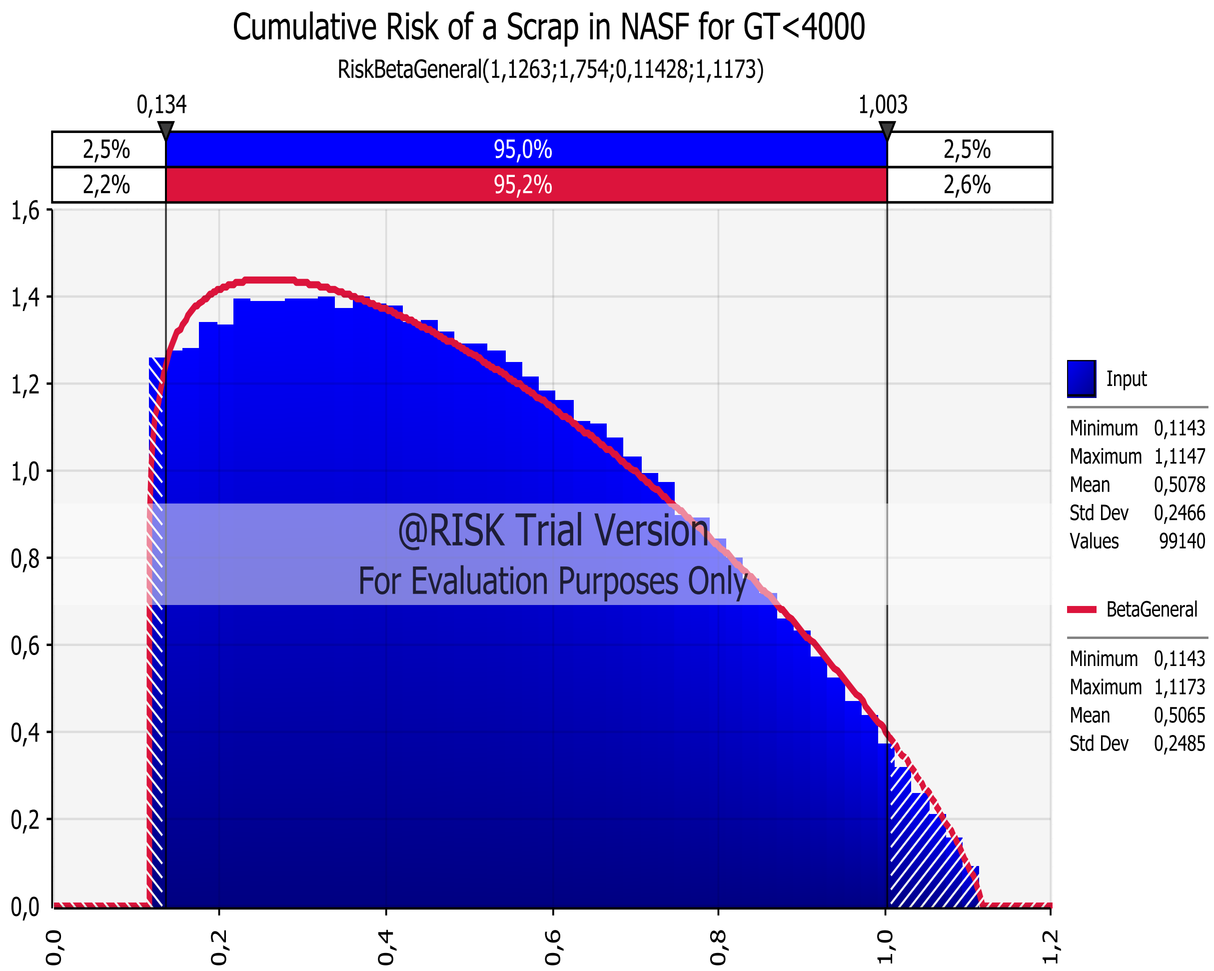


Figure 7.12: Distribution of PDP for a Scrap of a RoPax< 4,000GT with NASF

It must be remarked that the mean value of the PDP of a Scrap in specific class seemed to be 0.507 (Figure 7.12), whereas the cumulative risk for the cost in case of a Scrap found 0.168. The explanation for this difference is subjected to the fact that Lightship values can reach high levels (Figure 7.3) while ships which observed to be scrapped after their loss had small Lightships.

Finally, it was achieved to form the distribution of cost's cumulative risk that RoPax ships with 4,000GT and below follows (Figure 7.13). By interpreting this graph, the value of the PDP found to be 5.030. On the other hand, investigating data led us to the result that cumulative risk for the occurred incidents of NASF with respect to the cost was 4.660.

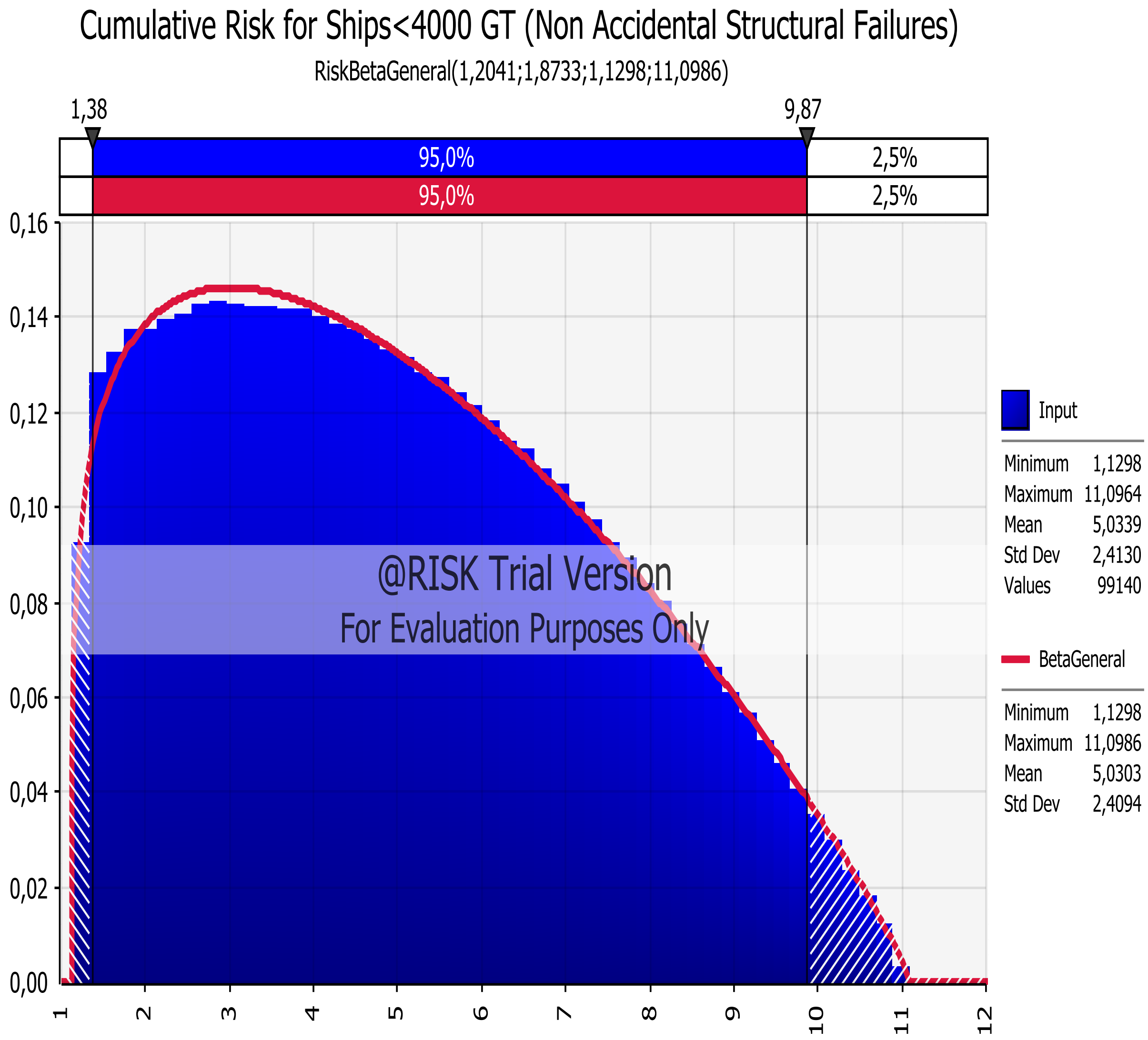


Figure 7.13: Distribution of PDP for RoPax Ships< 4,000GT with NASF

So, the total results are:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	4.438	4.442
Refloat	0.054	0.042
Scrap	0.168	0.507
Total	**4.660**	**5.030**

Table 7.1: Relative Potential Cost for the Small Class with NASF for each approach

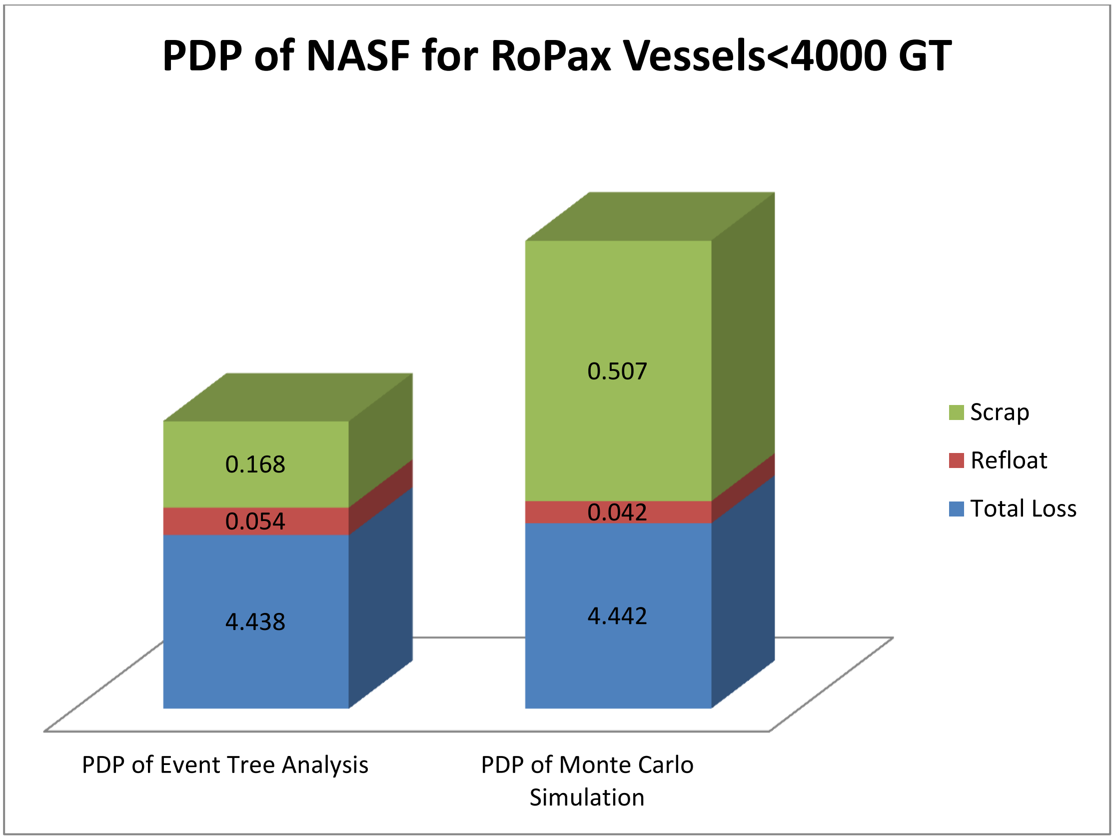


Figure 7.14: Cumulative Risks with respect to NASF for Small Class of RoPax Ships for each approach of analysis

Furthermore, for the better comprehension of each cumulative risk, it was decided to distinguish the Damage to Property in the aforementioned categories with respect to the initial cause of failure (Failures due to corrosion, Failures due to Fatigue). Consequently, the results for each category are presented below:

- *Small Class with Corrosion*

The outputs of Figure 7.7 and the assessed probability of 20.5% (Table 5.2) for having a Total Loss after a casualty for ships in specific category help us to estimate the distribution of Total Loss's cumulative risk (Figure 7.15).

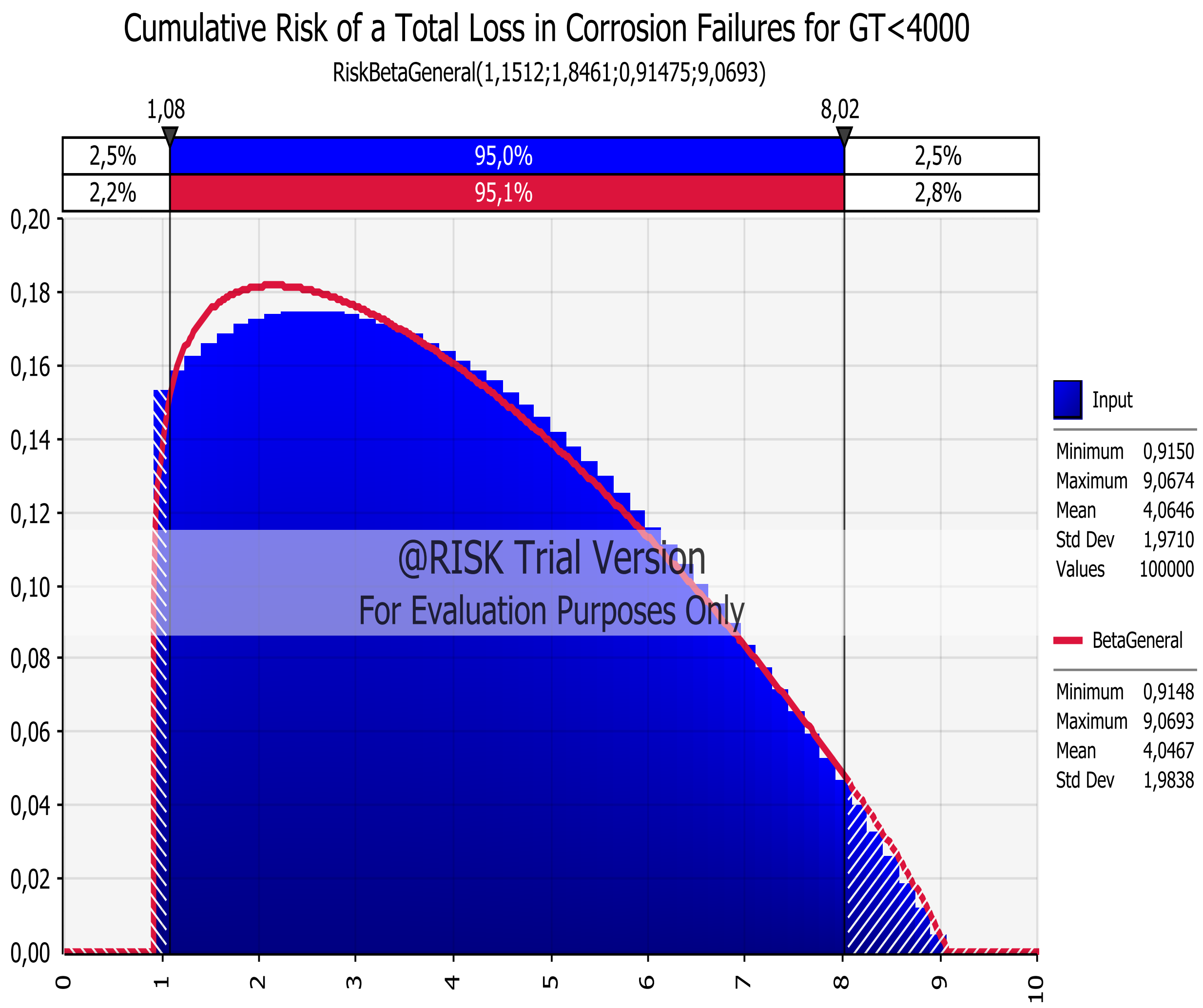


Figure 7.15: Graph shown the distribution of the cumulative risk for a Total Loss in corrosion Failures

A vital outcome that emerges from the above diagram (Figure 7.15) is that the expected value (mean) of the Distribution which illustrates the PDP is about 4.047. If this value is compared with the result of the respective Event Tree, which is 3.783 (Table 5.2), the conclusion that cumulative risk is a little bigger for all the fleet than NASF fleet can be easily reached.

Similarly, PDP distribution for a Refloat (Figure 7.16) was calculated with taking into consideration that Refloat probability had found about 2.56% for the specific category (Table 5.2).

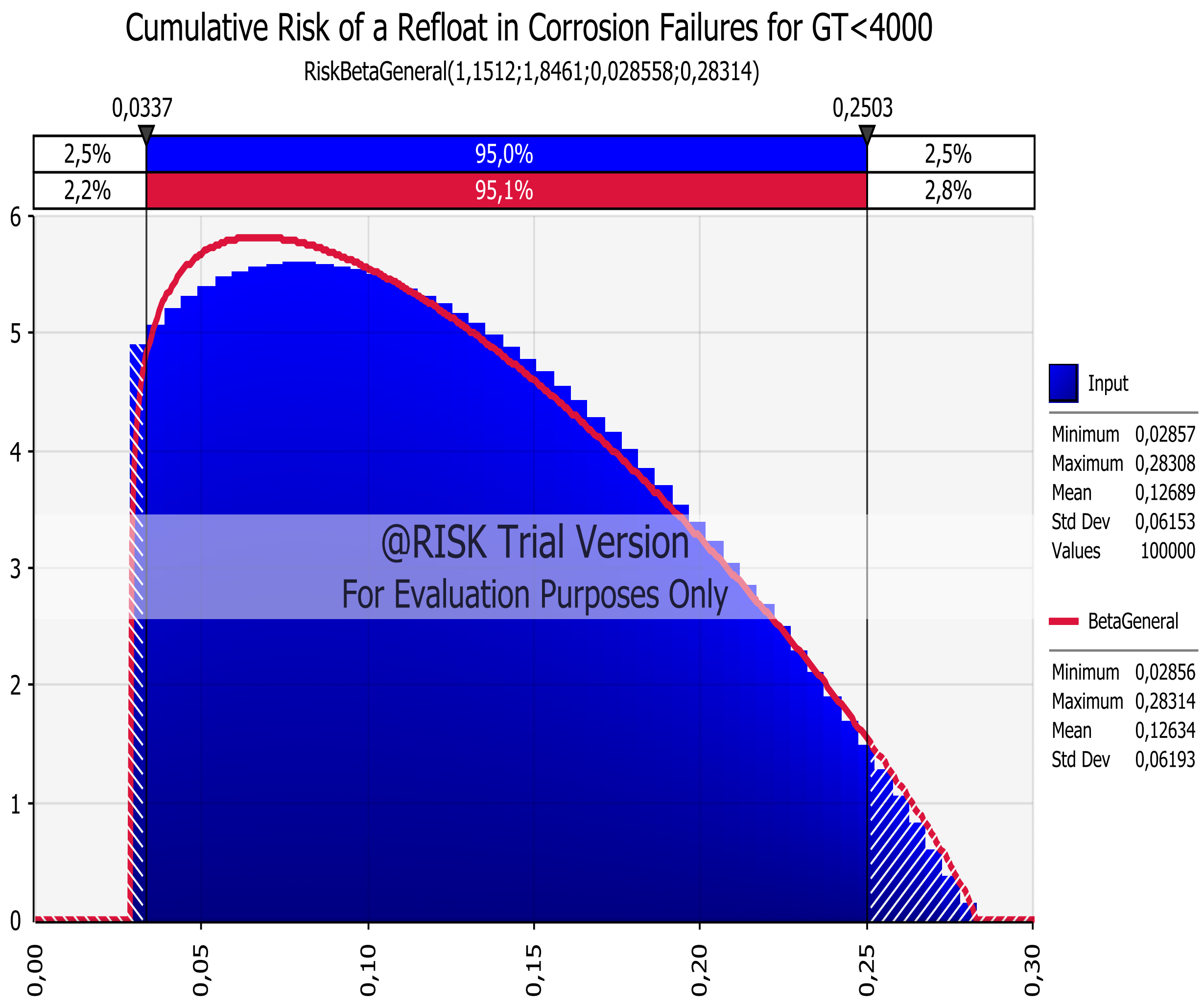


Figure 7.16: Features of PDP in case of a Refloat for Corrosion Failures

It is obvious that the expected value of the cumulative risk with respect to the cost when a vessel refloated is approximately 0.126, and its boundaries are between 0.029 and 0.283. The value of cumulative risk that assessed from the concerned Event Tree was 0.158. This discrepancy as it was mentioned before is due to the small Lightship of the one recorded casualty with these characteristics.

Cumulative risk of a Scrap has figured too (Figure 7.17), as the probability of this incident's degree of severity was also 2.56%.

Figure 7.16 shows that the mean value of the assessed distribution is circa 0.501 while the cumulative risk of the existent casualties which were accompanied by Scrap is 0.198. The reason for this divergence is the difference between the average of Lightship of all the fleet (Figure 7.3) and the small Lightship of the vessel that is found to be scrapped after the casualty in specific kind of failure.

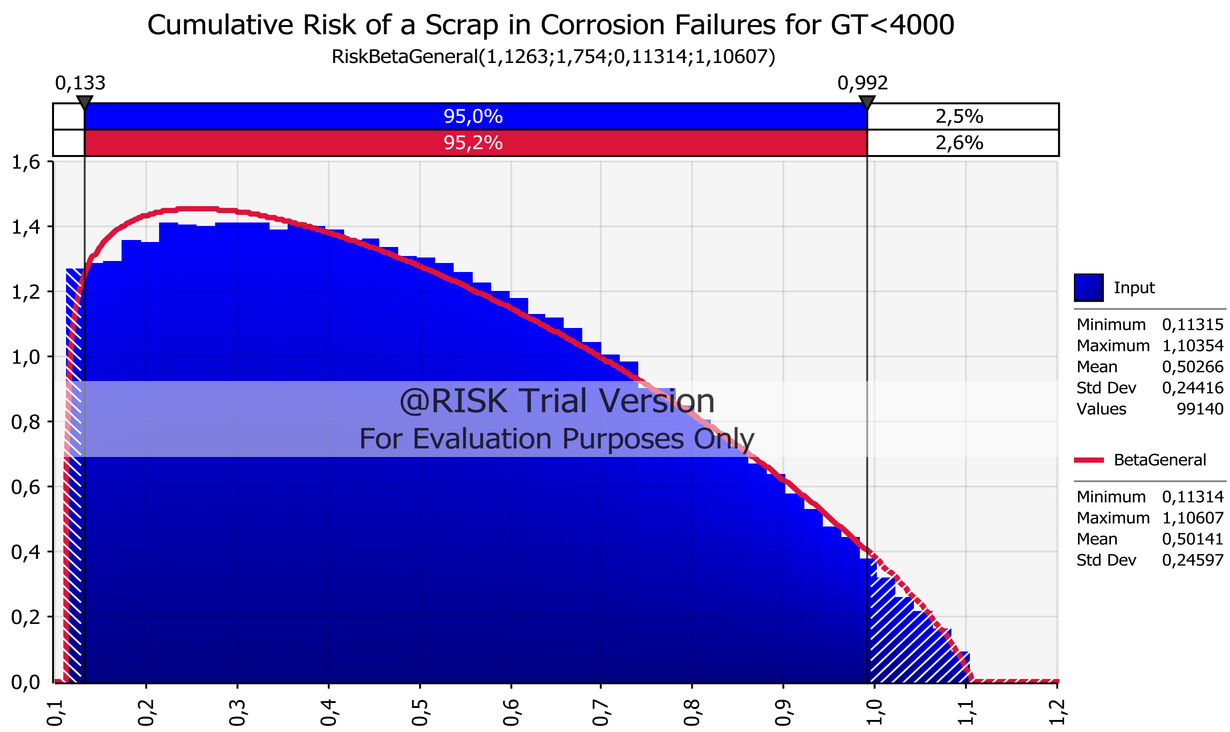


Figure 7.17: Distribution of PDP for a Scrap in corrosion failures and small class of RoPax ships

Eventually, the total cumulative risk for corrosion failures in ships under 4,000GT was calculated with the aid of the fitted allocation (Figure 7.18) to the appreciated datum.

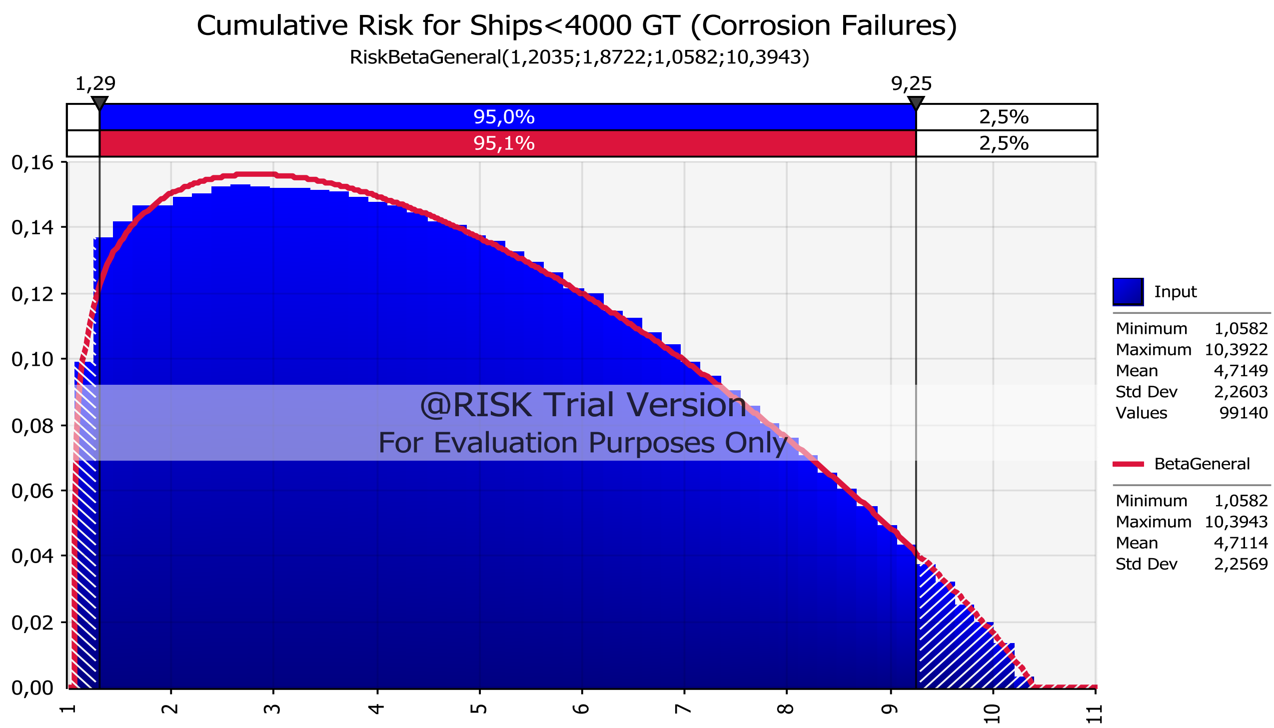


Figure 7.18: Graph of the cumulative risk for Ships<4000GT with corrosion failures

Investigating reports gave us the outcome that ships with 4,000 GT and below which suffered from corrosion failures run a risk with cumulative risk 4.139 (Table 5.2). Contrariwise, taking into account the whole fleet, it was found that an estimated value of the cumulative risk in this category is 4.711.

Summarily, the above results are presented below:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	3.783	4.047
Refloat	0.158	0.126
Scrap	0.198	0.501
Total	**4.139**	**4.711**

Table 7.2: Relative Potential Cost for the Small Class with Corrosion for each kind of analysis

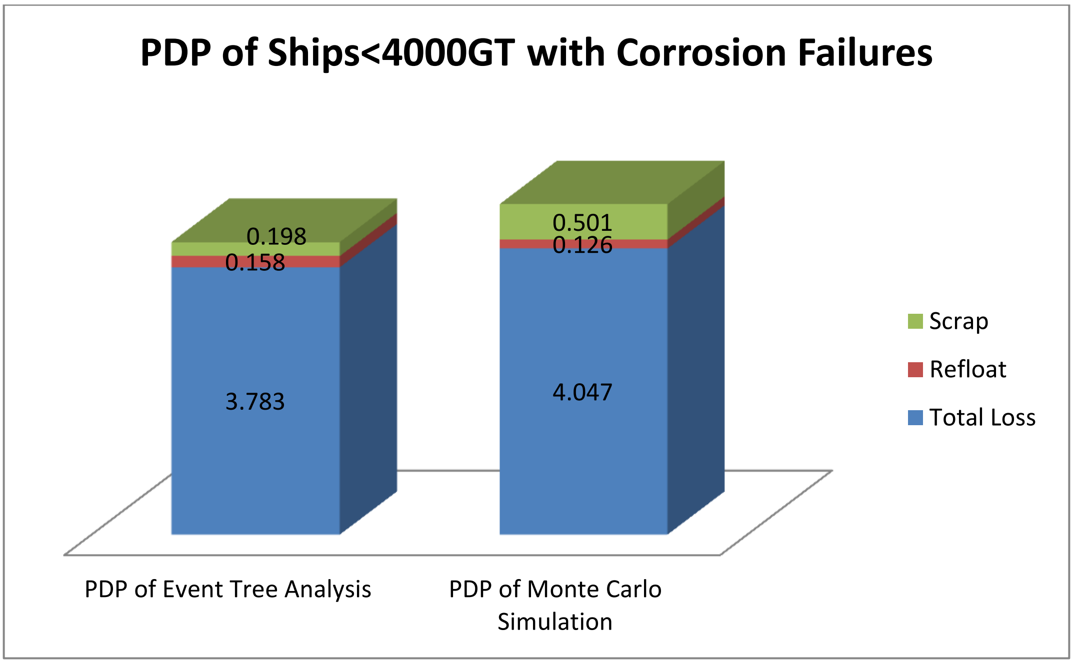


Figure 7.19: Cost's cumulative risks for Small class for corrosion failures for each kind of analysis

- *<u>Small Class with Fatigue Failures</u>*

Monte Carlo Simulation implemented for this category too. Having taken into consideration the probability that emerged for a Total Loss after the Event Tree analysis for current category, this was 24.67% (Table 5.5), and the outcomes of Cost allocations, was easy to form the distribution for the Potential Damage to Property for a Total Loss (Figure 7.20).

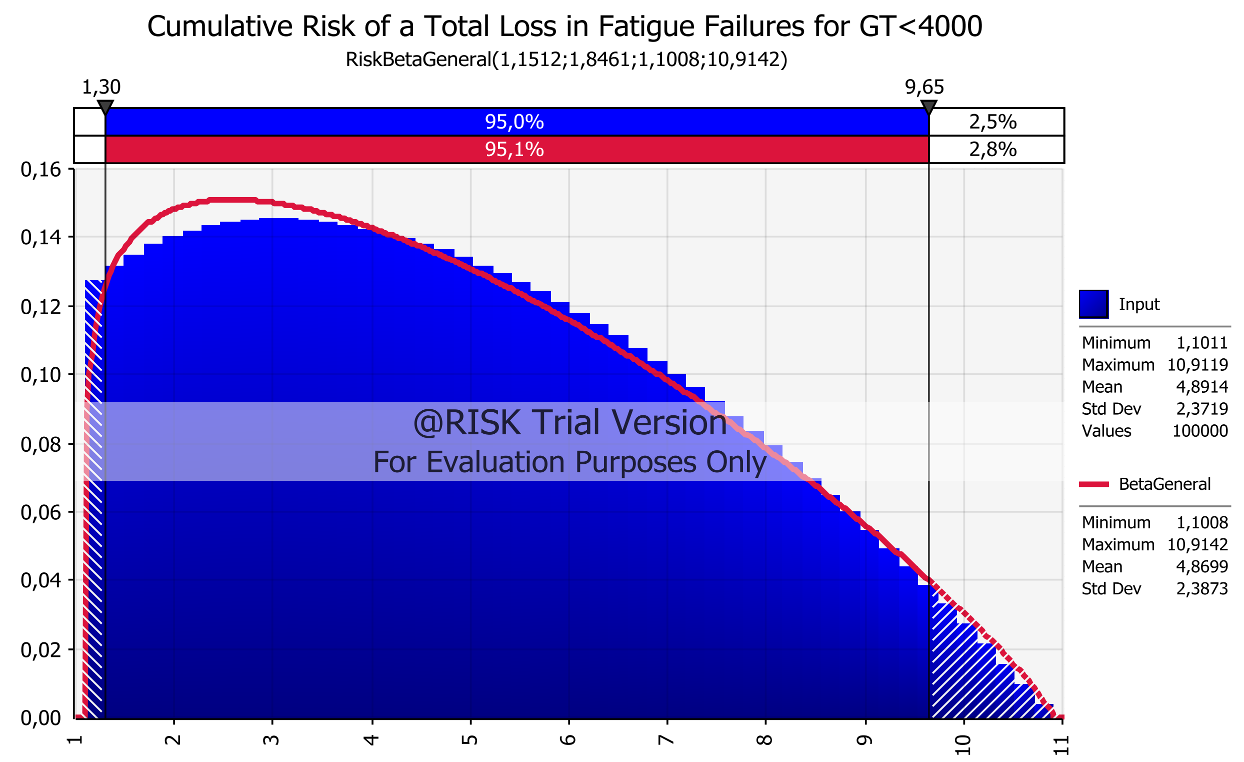


Figure 7.20: Features of Cumulative Risk of a Total Loss in specific category

Undoubtedly, the above graph (Figure 7.20) can give us the expected value of the cumulative risk in an occasion of an incident which would result loss of the ship due to a fatigue failure. So, it can be observed that this value is about 4.87. On the other hand, it is known that considered accidents of a previous analysis (Event Tree analysis) gave us a suchlike value for similar cases that was 4.755 (Table 5.5).

The other factor which needed to be ascertained if it was accurate, was the cumulative risk of a Scrap. As it has already been mentioned, this degree of severity refers to the loss of ship but with its dissolution so as the company have a lower damage due to the profit of the scrap. The probability to occur something that in this determinate category of RoPax ships, was calculated in Risk Analysis and found 2.6% (Table 5.5). Because of the cost distribution for a Scrap and the estimated probability, it was feasible to comprehend how the cumulative risk allocates in such category (Figure 7.21).

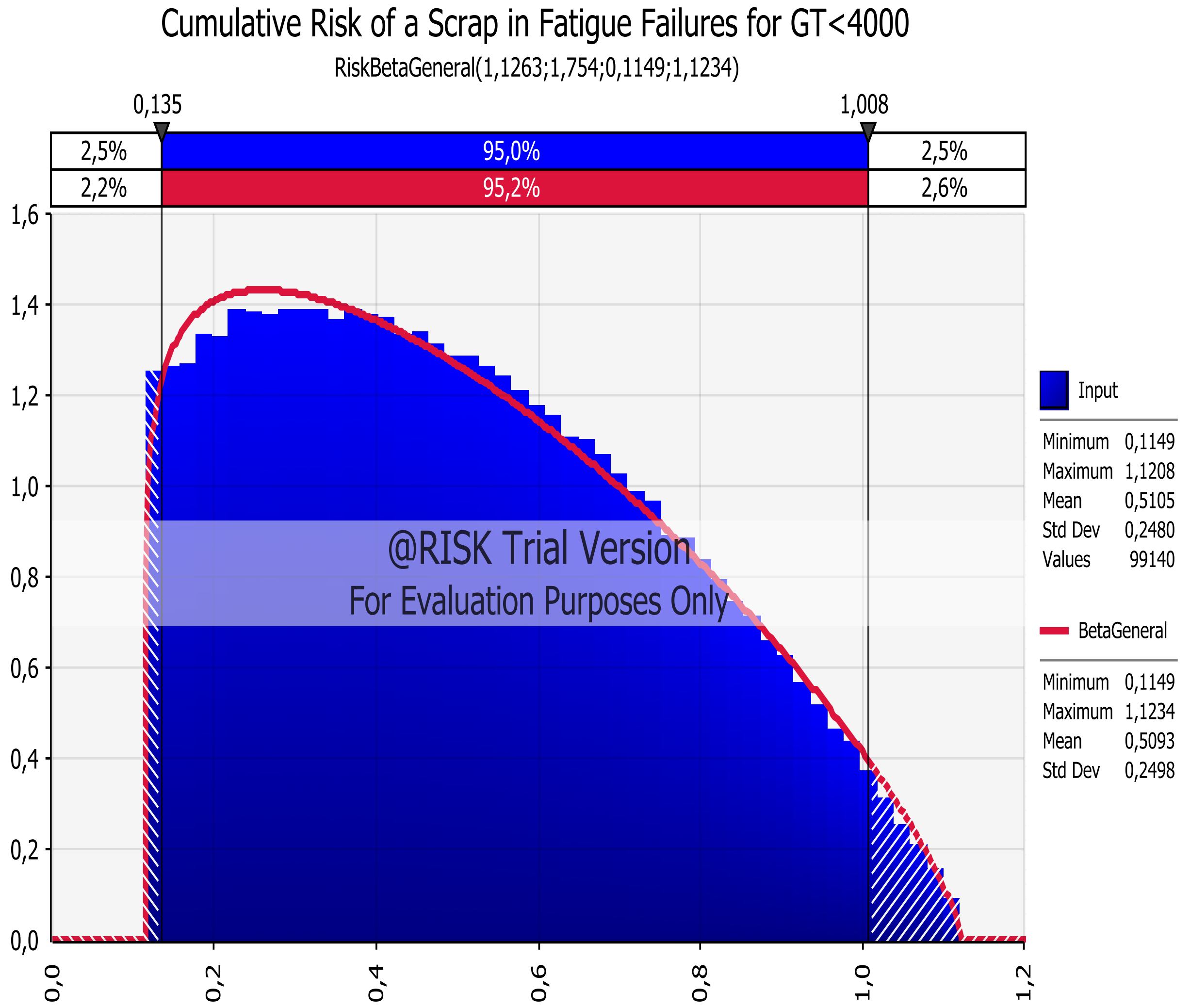


Figure 7.21: Histogram and distribution of the PDP for a Scrap in fatigue failures for the small class

As it was expected because of the few accidents that lead to this degree of severity, there is a divergence between the mean value of cumulative risk that can be read by respective diagram, it is 0.509 (Figure 7.21) and the expected value of PDP that assessed on Event Tree analysis which was 0.154 (Table 5.3).

Lastly, the way that the cumulative risk of Ropax vessels with 4,000GT and below with fatigue failures is allocated, was found and its figure is illustrated below (Figure 7.22).

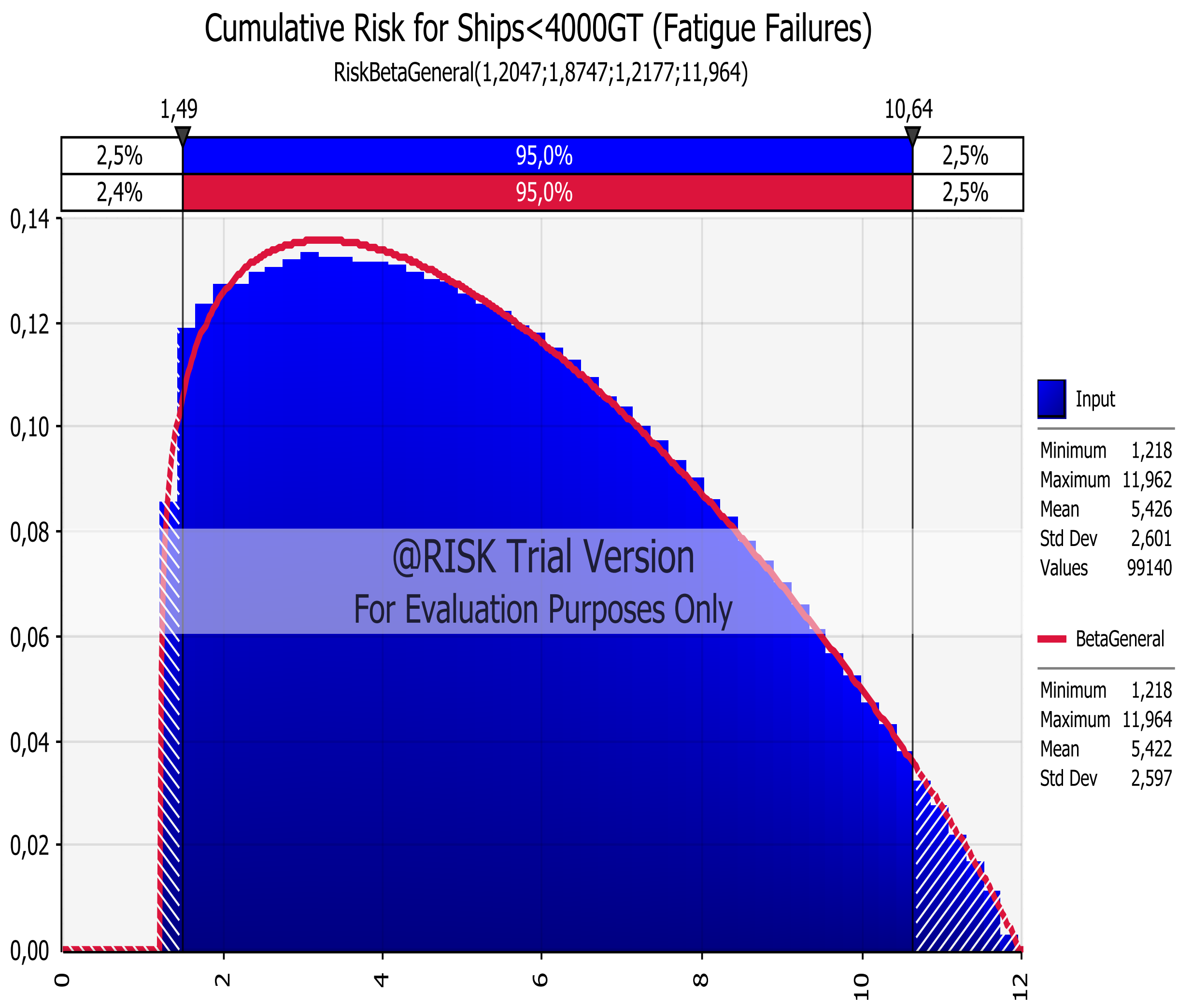


Figure 7.22: Distribution of the PDP for RoPax Ships< 4000 GT in fatigue failures

The relation between the values that derived by Monte Carlo Simulation and the Event Tree Analysis is a little different due to the fact that scrap was a rare condition on the investigating reports and the results were not so precise. According to Monte Carlo simulation the cumulative risk was 5.422 (Figure 7.22) while the predefined risk contribution estimated about 4.909.

The aggregated results are:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	4.755	4.870
Scrap	0.154	0.509
Total	**4.909**	**5.422**

Table 7.3: Relative Potential Cost for the Small Class with Fatigue Failures for each approach of Risk analysis

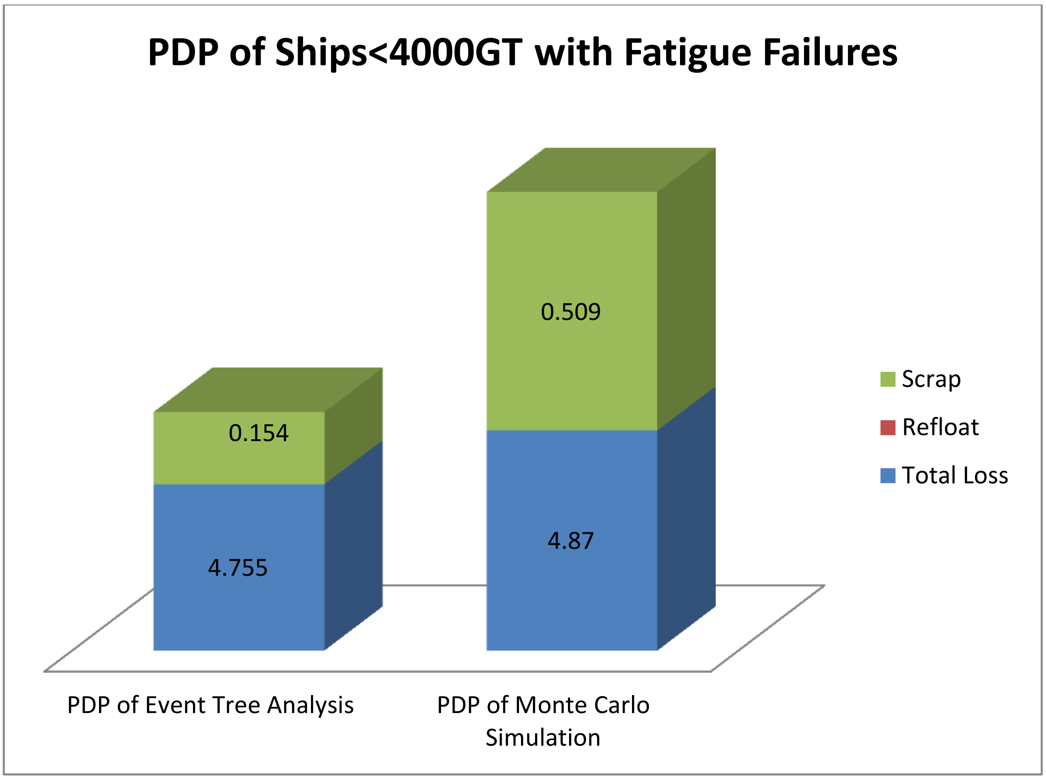


Figure 7.23: Cost's cumulative risks for the Small Class with Fatigue Failures for each approach of analysis

<u>RoPax Ships with 4,000 GT and above (Large class)</u>

It is an undisputed fact that the larger the ship is the more expensive it is. So, the difference of the cost between small and large class of RoPax vessels is absolutely comprehensible.

The distribution of the cost for the loss of a ship after an incident is illustrated in Figure 7.24.

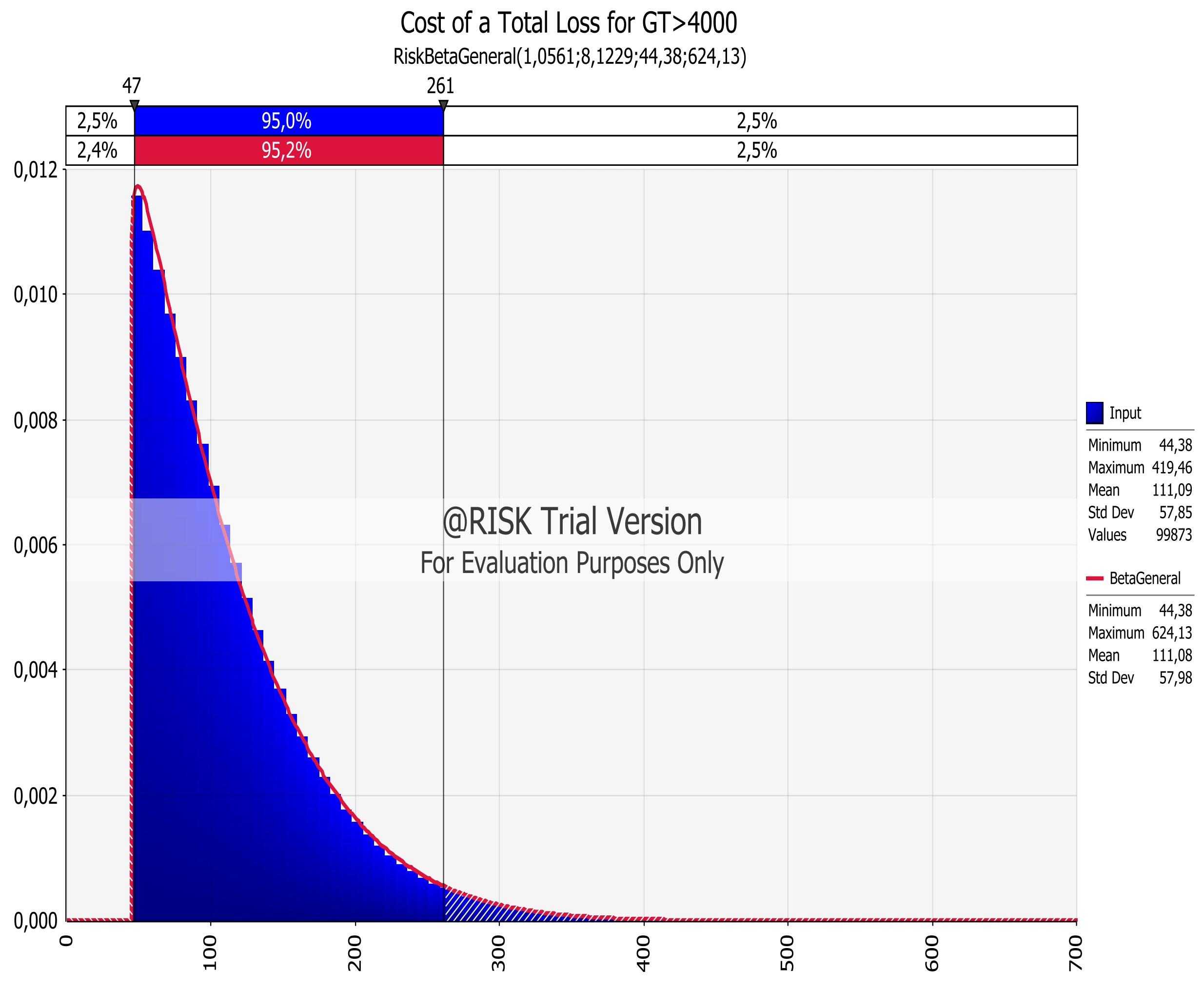


Figure 7.24: Distribution of the cost for a Total Loss of a RoPax> 4,000GT

It must be mentioned that while values of the simulation were 100000 in this occasion too, filters with respect to GT distribution and the formula of the cost are used so as not have been taken values that are not responsive to the reality. For that reason, values label of the Figure 7.21 shows fewer values. It can also be noticed that the mean cost of the property is about 111.08million euros.

Two more distributions that were useful to be found for the process of current analysis concerned the cost of a Refloat (7.25) and the cost of a Scrap (7.26).

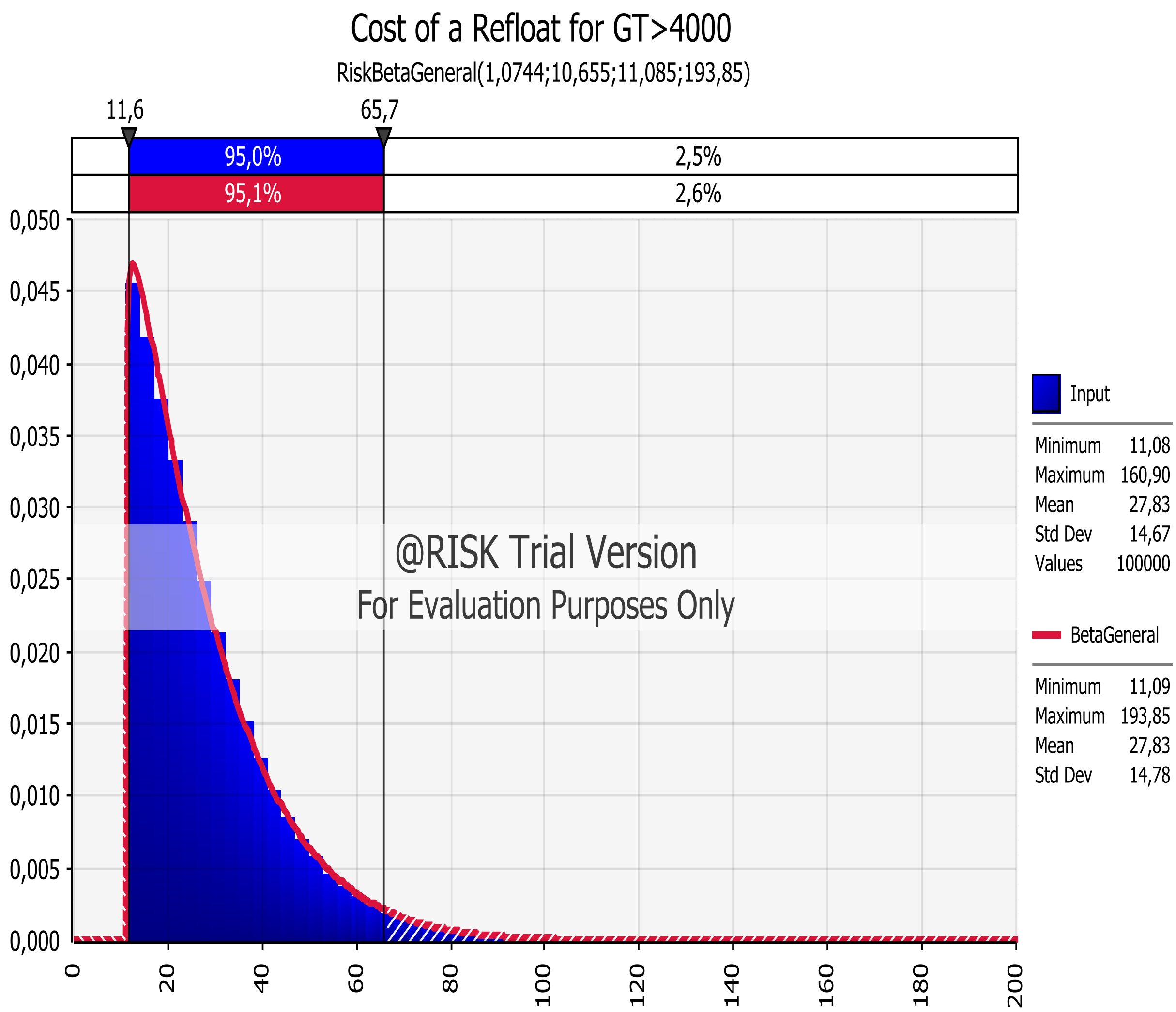


Figure 7.25: Distribution of the cost for a Refloat of a RoPax> 4,000GT

The lowest cost that a shipping company will have in a case of Refloat seems to be 11.09 million euros whereas the highest amount of money that will lose reaches 193.5 million euros (Figure 7.25).

By interpreting Figure 7.26, the results that the average cost of a ship that after being sunk will go for Scrapping, is equal to 110.51 million euros. It is meaningless to say that this distribution also follows Beta General Distribution, something that is proved to be very common for all the cost distributions.

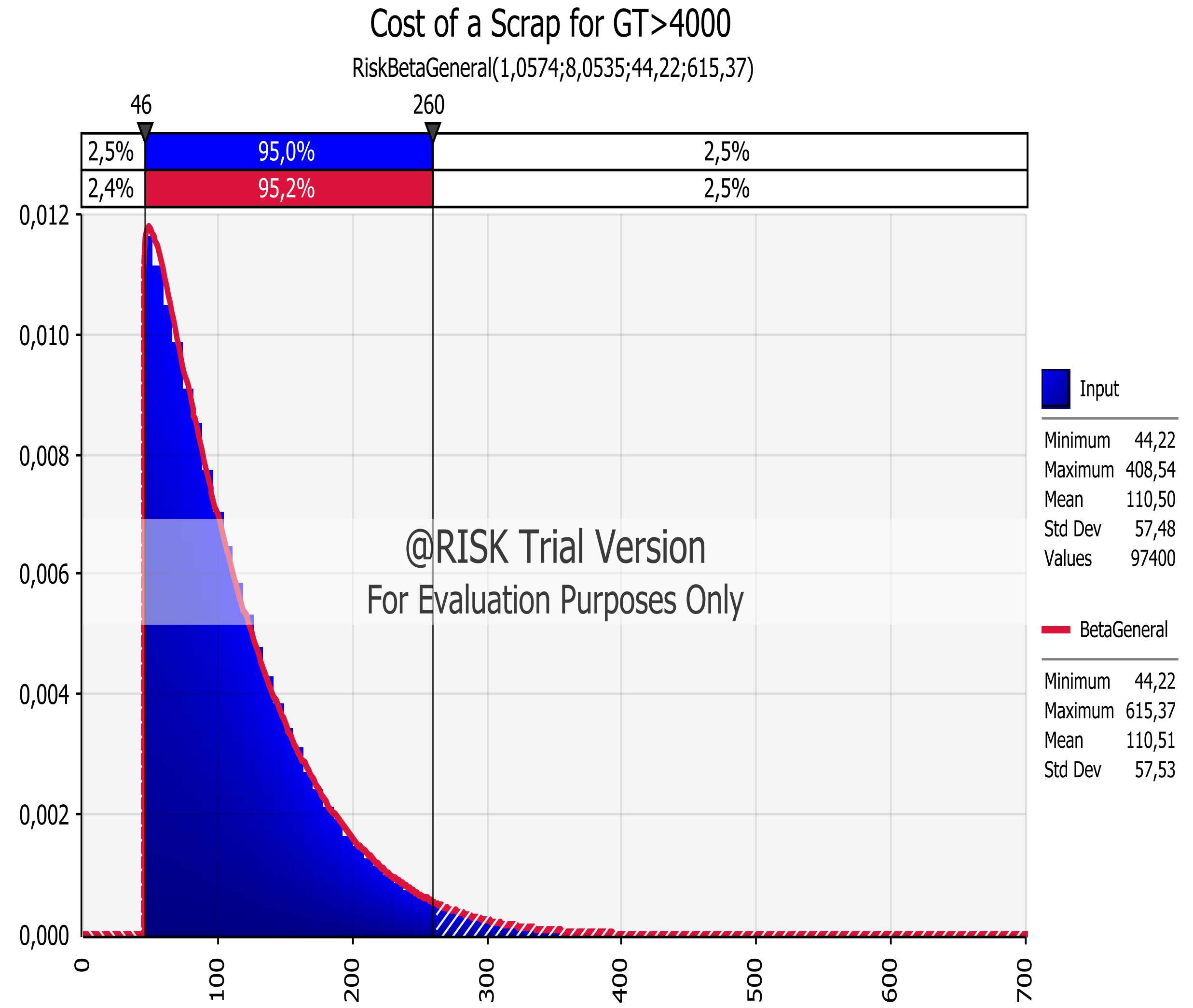


Figure 7.26: Distribution of the cost for a Scrap of a RoPax> 4,000GT

The SEAWEB reports and the additional information provided by the maritime community contributed to the assessment of the risk with respect to the Damage to Property.

As a consequence, the estimation of the distribution of cost's cumulative risk for the loss of a ship was attempted. Probability of losing the ship was found to be 7.14% and the distribution resulted to follow Beta General Distribution (Figure 7.27).

Potential Damage to Property of the recorded casualties evaluated 5.205. That value seems to differ a lot by the mean of the cumulative risk of a total loss, which calculated basing on whole fleet's ship with Gross Tonnage higher than 4,000, and its value is 7.935 (Figure 7.27).

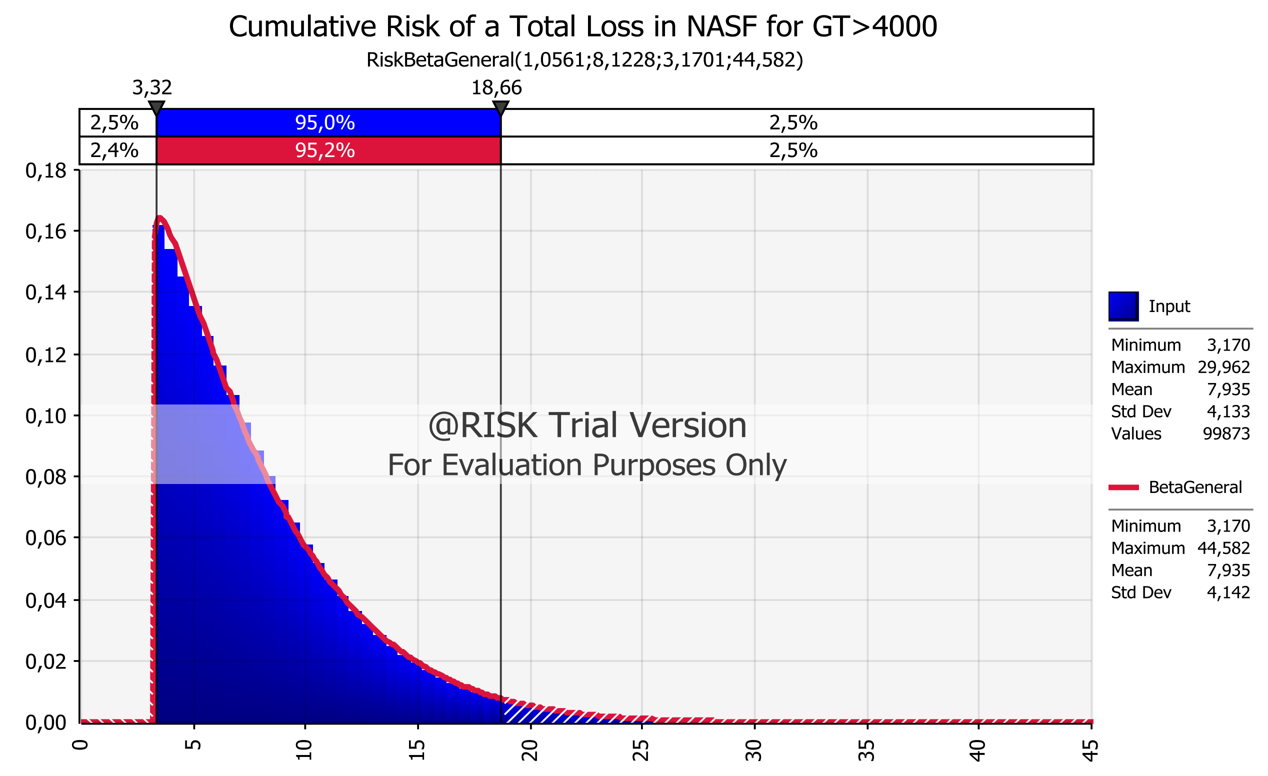


Figure 7.27: Distribution of PDP for a Total Loss of a RoPax> 4,000GT with NASF

For the achievement of determining cumulative risk of a Refloat in relation to the cost, the possibility of its occurrence in NASF counted (3.57%). So, its distribution is shown in Figure 7.28.

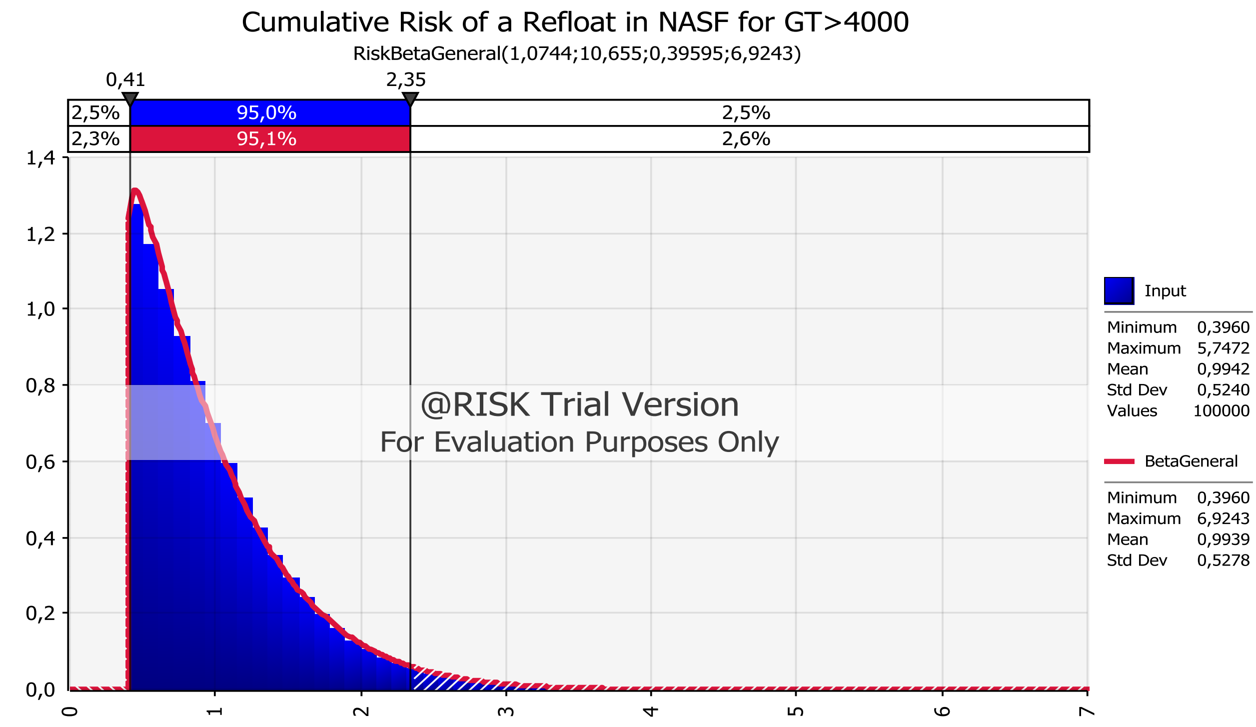


Figure 7.28: Distribution of PDP for a Refloat of a RoPax> 4,000GT with NASF

The analysis of the reports that concerned NASF incidents gave us the impression that cumulative risk of the damage to property for a Refloat was 0.542. But Monte Carlo simulation suggested that specific value is 0.994 (Figure 7.28).

Moreover, it must be mentioned that probability of a Scrap for NASF in large class of RoPax ships was 1.12% according to the information given. Having used this probability and the outputs of the cost distribution for the specified category, the determination of the allocation of cumulative risk for a Scrap for the large class of ships with NASF did not present any difficulty (Figure 7.29).

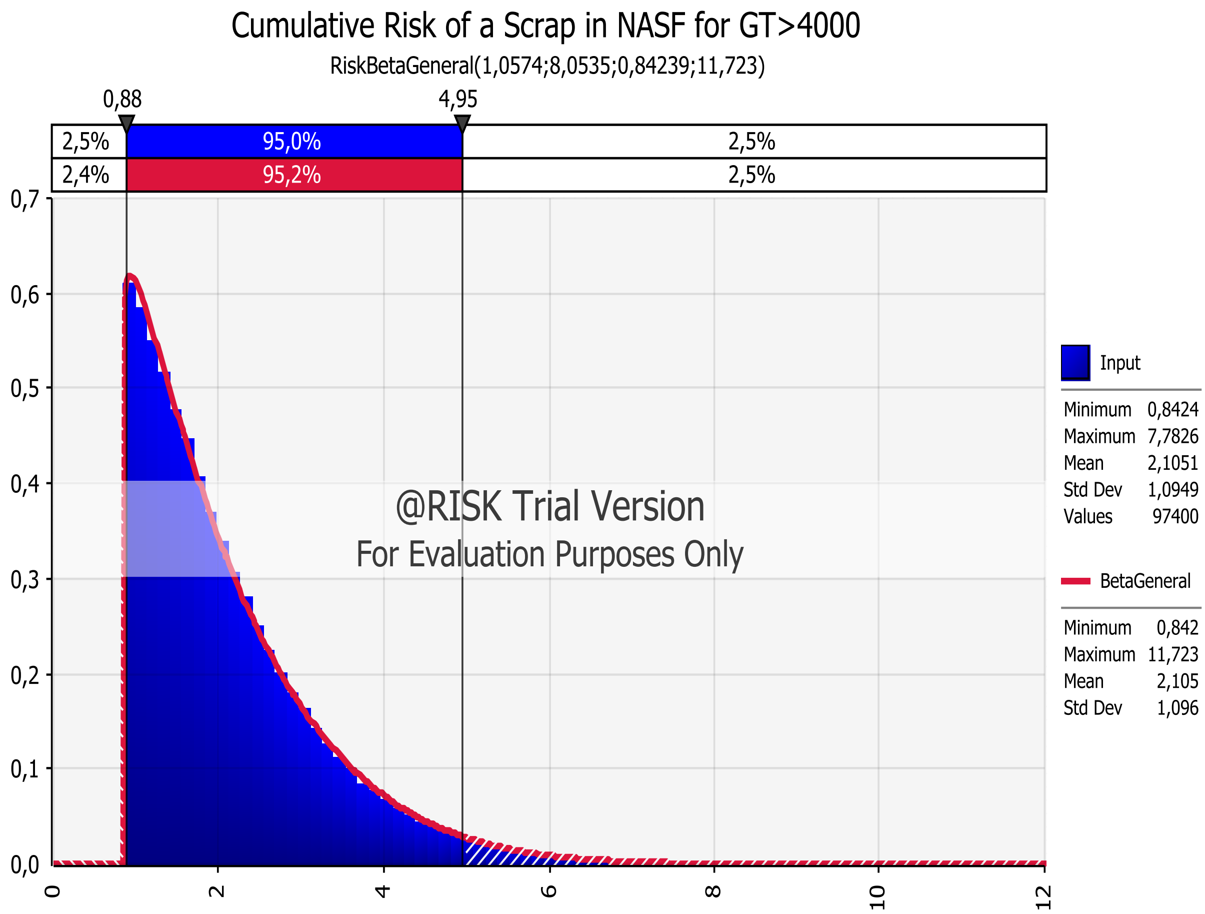


Figure 7.29: Distribution of PDP for a Scrap of a RoPax> 4,000GT with NASF

It is derived by above graph (Figure 7.29) that PDP for a Scrap is about 2.105, while the value that emerged by the investigating data of NASF accidents was 0.936.

Eventually, the distribution of the risk that a RoPax ship with 4,000GT and above runs after a Non Accidental Structural Failure was defined (Figure 7.30).

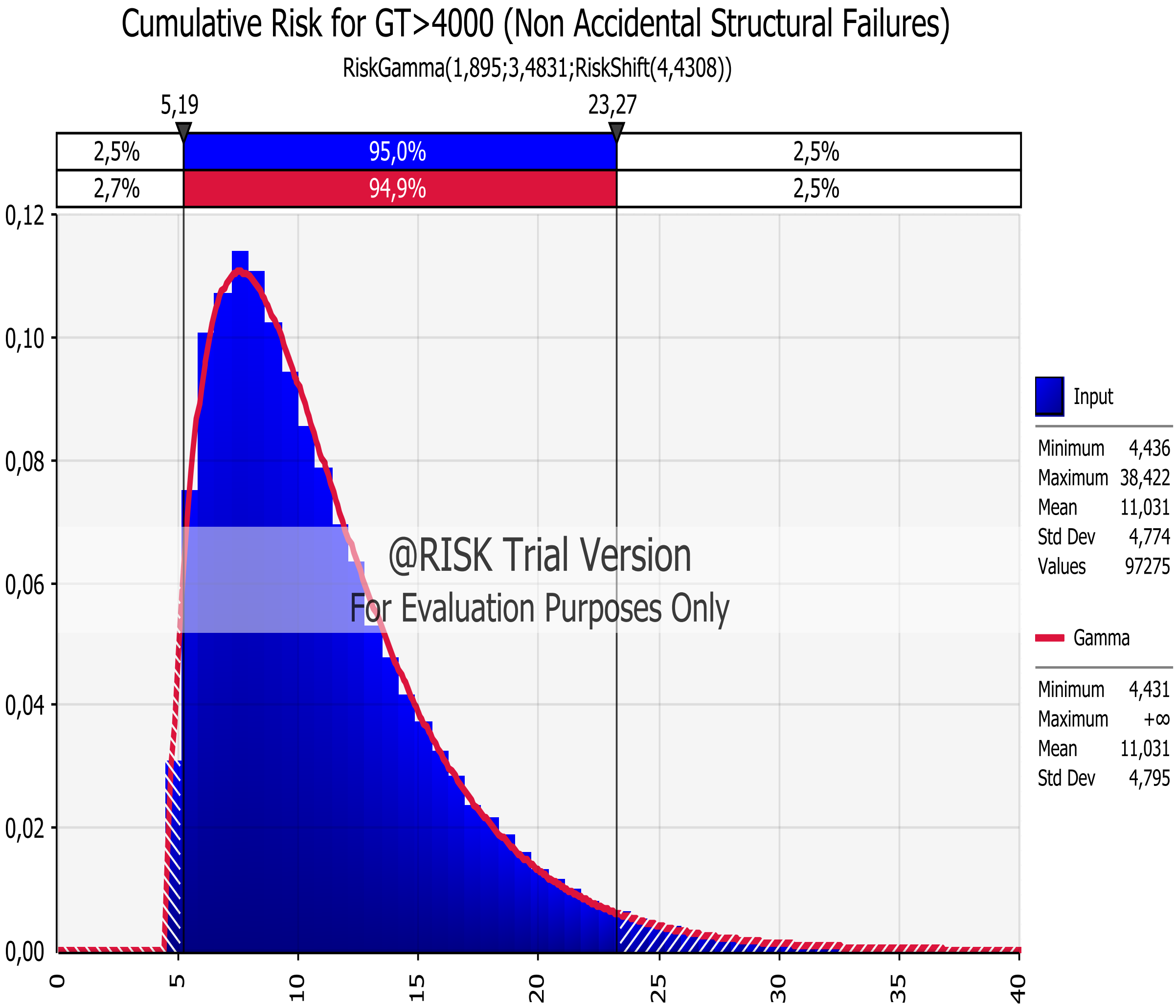


Figure 7.30: Distribution of PDP for RoPax Ships> 4,000GT with NASF

It can be observed that expected value of the distribution that is illustrated in Figure 7.23 is 11.031. However, the analysis of the reports for the Non Accidental Failures for the large class of RoPax vessels had led us to the conclusion that PDP was 6.683.

The above outcomes are presented below:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	5.205	7.935
Refloat	0.542	0.994
Scrap	0.936	2.105
Total	**7.23**	**11.031**

Table 7.4: Relative Potential Cost for the Large Class with NASF for each approach of analysis

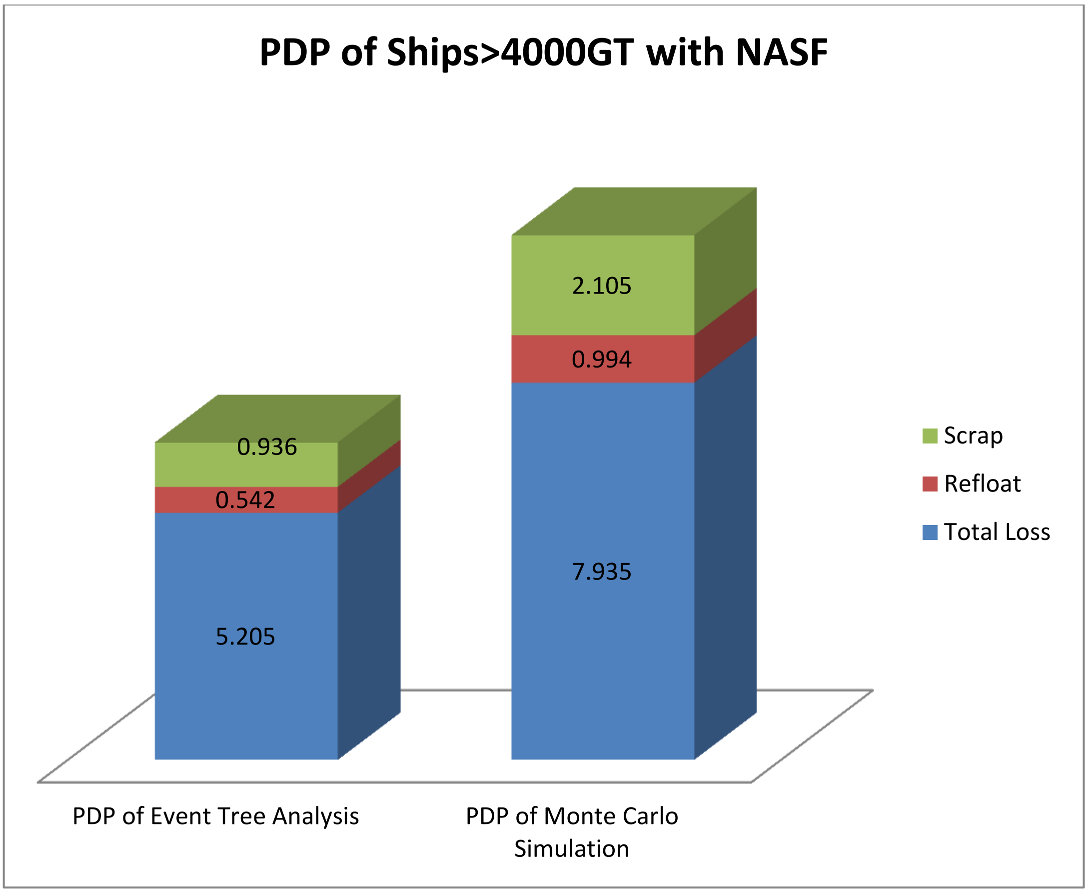


Figure 7.31: Cost's cumulative risks for the Large Class with NASF for each approach of Analysis

So as to achieve better correlation and verification of the outcomes between Risk Analysis and Monte Carlo simulation, two categories distinguished.

- *Large Class with Corrosion*

For the evaluation of the cumulative risk for a Total Loss in relation to the cost, the probability, which estimated by the Event Tree analysis, was taken (Table 5.2). So, combining the probability with the specific cost distribution, help us to find how the potential damage to property is allocated (Figure 7.32).

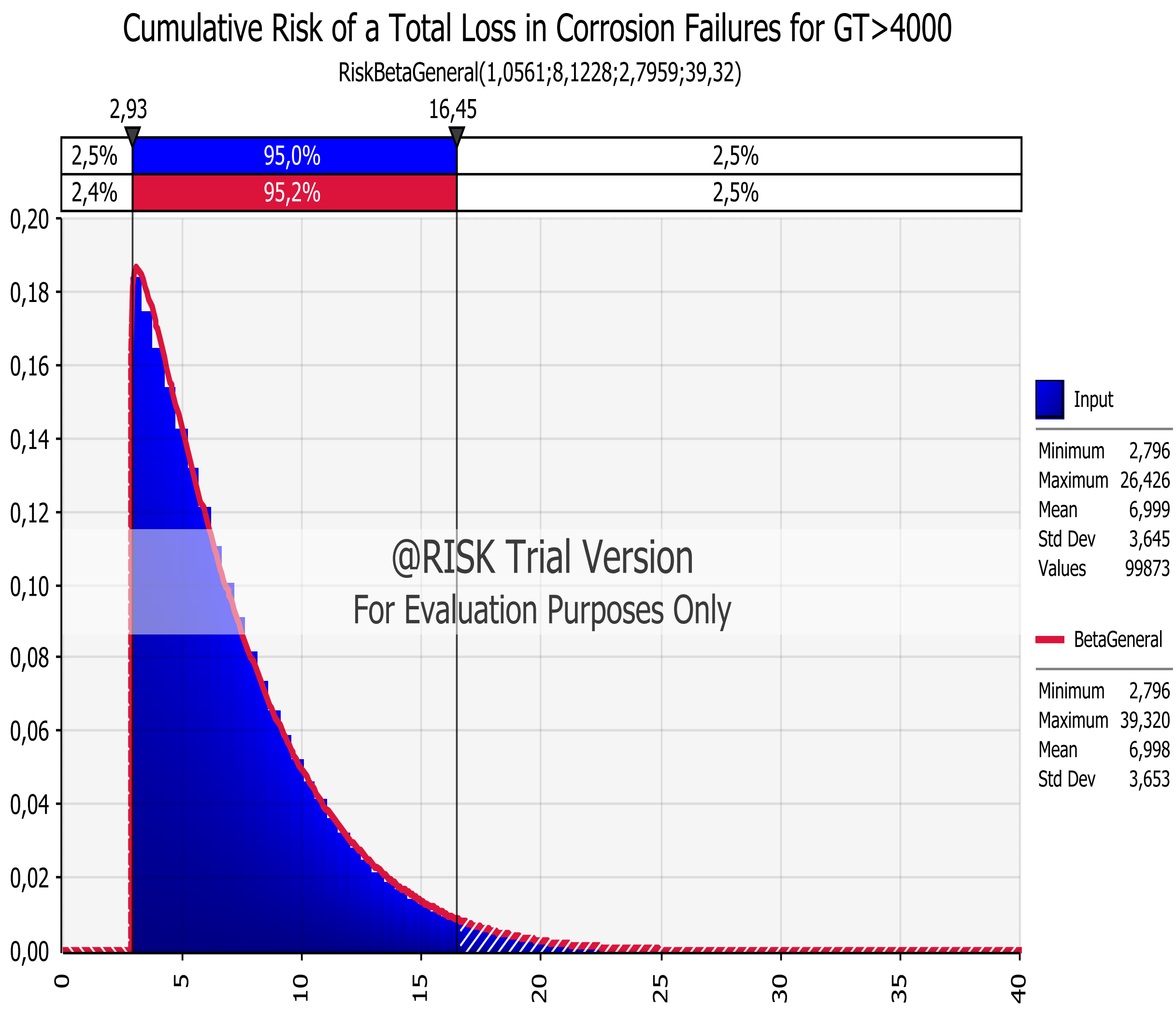


Figure 7.32: Distribution of PDP for a Total Loss of a RoPax> 4000GT with corrosion failures

The expected value of current cumulative risk seems to be 6.998 (Figure 7.32) while Event Tree analysis led us to the result that PDP of a Total Loss is equal to 3.150 (Table 5.2). The difference between these two values is imperative, but it is quite reasonable as the values of whole fleet's Gross Tonnage are higher than those which suffered from a NASF casualty. As a consequence, costs and cumulative risks vary a lot for each fleet's ships.

PDP distribution was estimated in cases of Refloat too (Figure 7.33). Consequently, the mean value of the cumulative risk for a Refloat with regards to the cost evaluated approximately 0.863. Contrariwise, the corresponding value assessed from the Event Trees that it was 0.372 (Table 5.2).

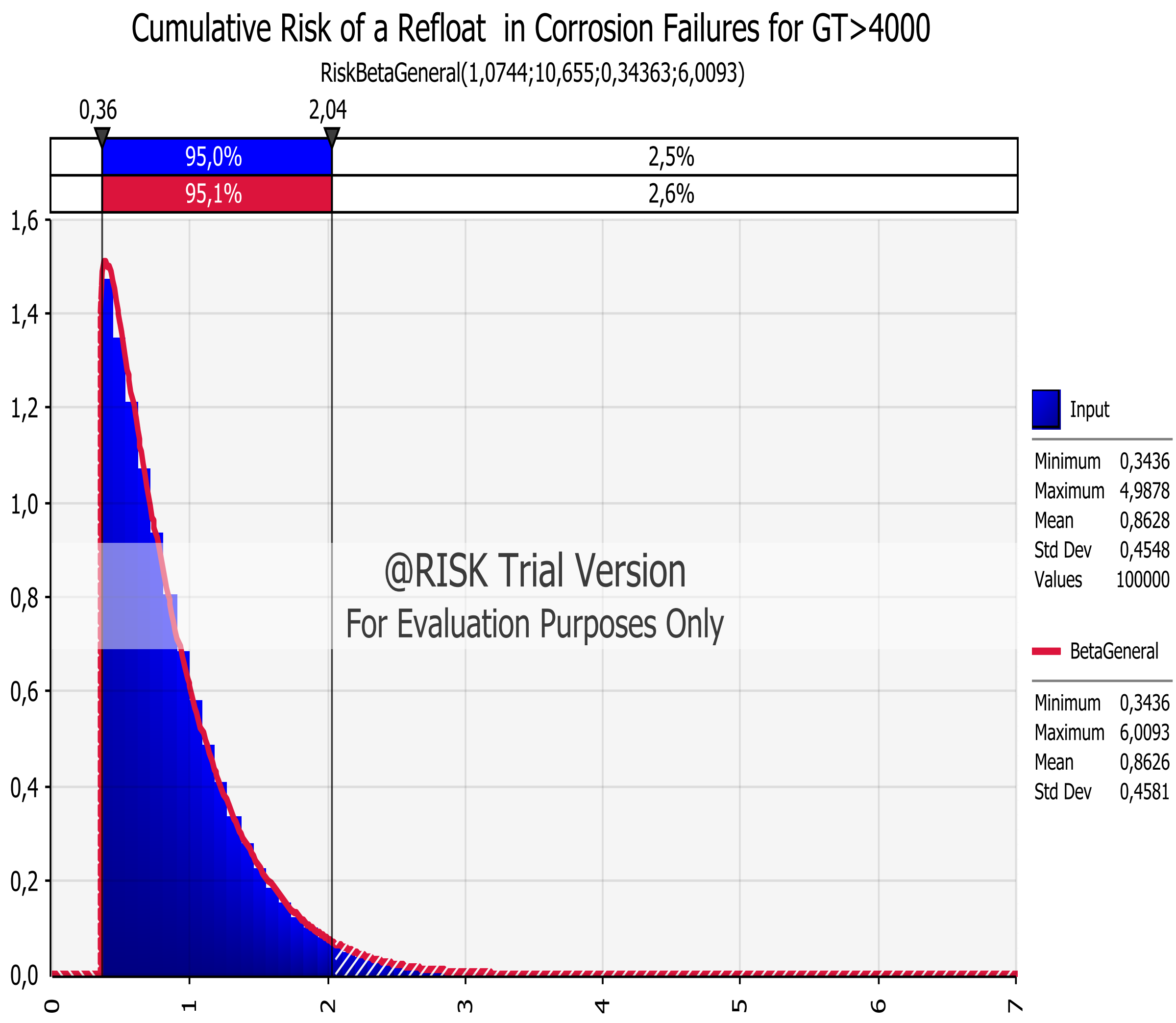


Figure 7.33: Distribution of PDP for a Refloat of a RoPax> 4000GT with corrosion failures

Therefore, there was the adequate information for the formation of the distribution which shows cumulative risk values for RoPax vessels bigger than 4,000GT (Figure 7.34).

Outcomes of current graph (Figure 7.34) urge us to create the perception that the mean value of the PDP for corrosion failures is 7.859. Unlikely, Event Tree analysis for corrosion failures in Ships>4,000 GT resulted that the expected value of such cumulative risk is 3.522.

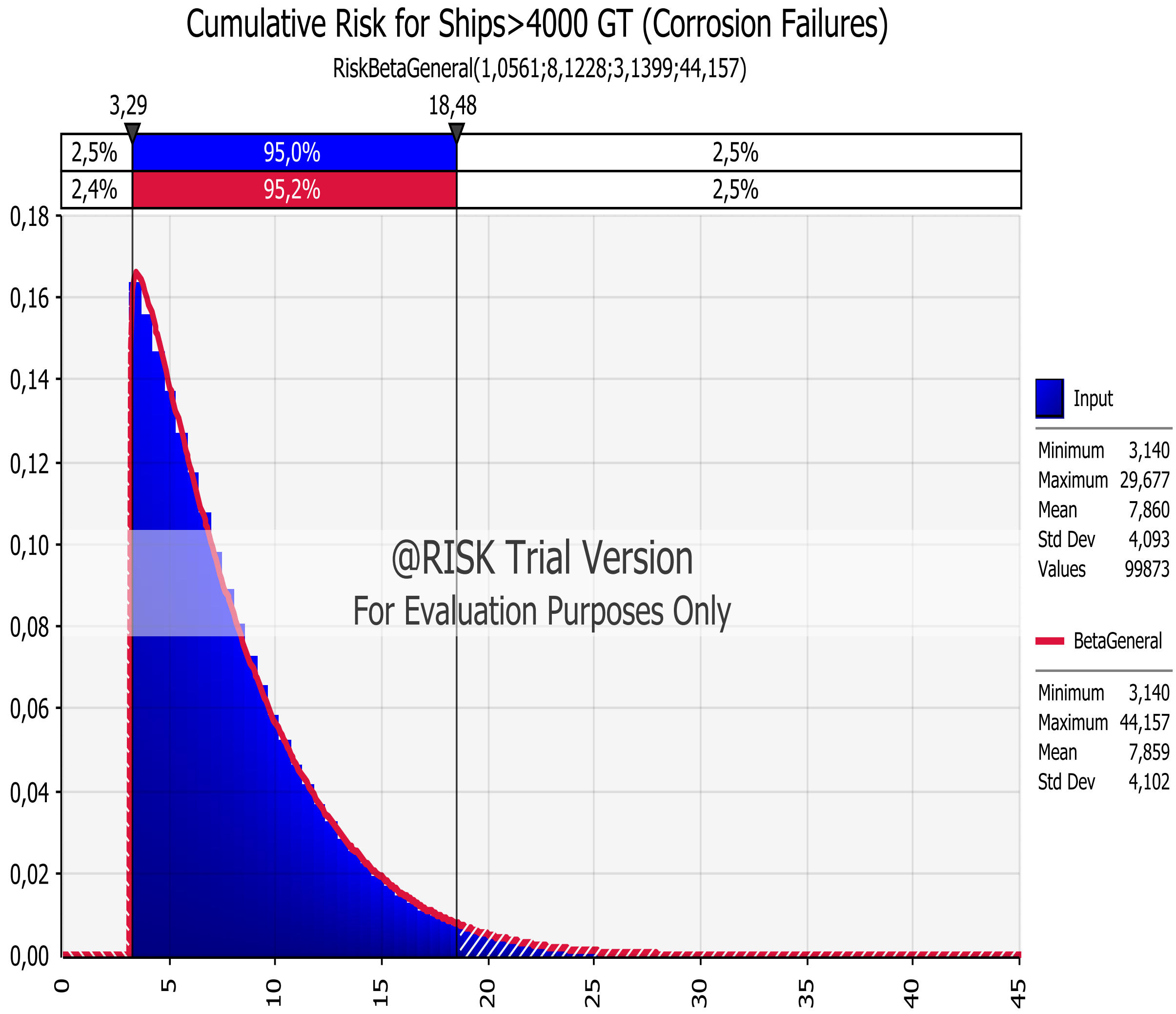


Figure 7.34: Distribution of the PDP for RoPax Ships< 4,000 GT in fatigue failures

The differences of the estimated cumulative risks are listed below:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	3.150	6.998
Refloat	0.372	0.863
Total	**3.522**	**7.859**

Table 7.5: Relative Potential Cost for the Large Class with corrosion failures for each approach of analysis

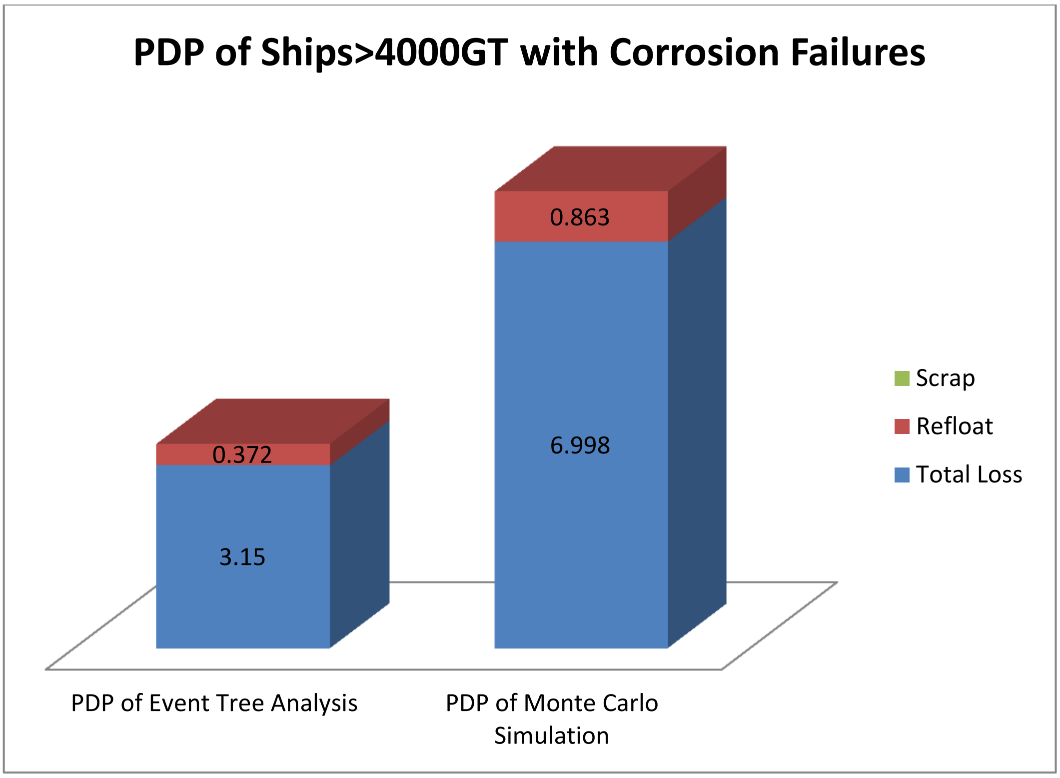


Figure 7.35: Cost's cumulative risks for the Large Class with corrosion failures for each approach of Analysis

- *Large Class with Fatigue Failures*

Cumulative risk allocation of a Total Loss with respect to the cost was estimated in this category too (Figure 7.36), as the probability for the occurrence of a Total Loss was about 7.7% (Table 5.5).

The previous Risk Analysis (Chapter 5) gave the indicative value of 6.550 (Table 5.5) whilst the graph below (Figure 7.36) mentions that the expected value of the Potential Damage to Property in the occasion of a Total Loss is 8.554. This means that the risk is little bigger if the whole fleet is considered.

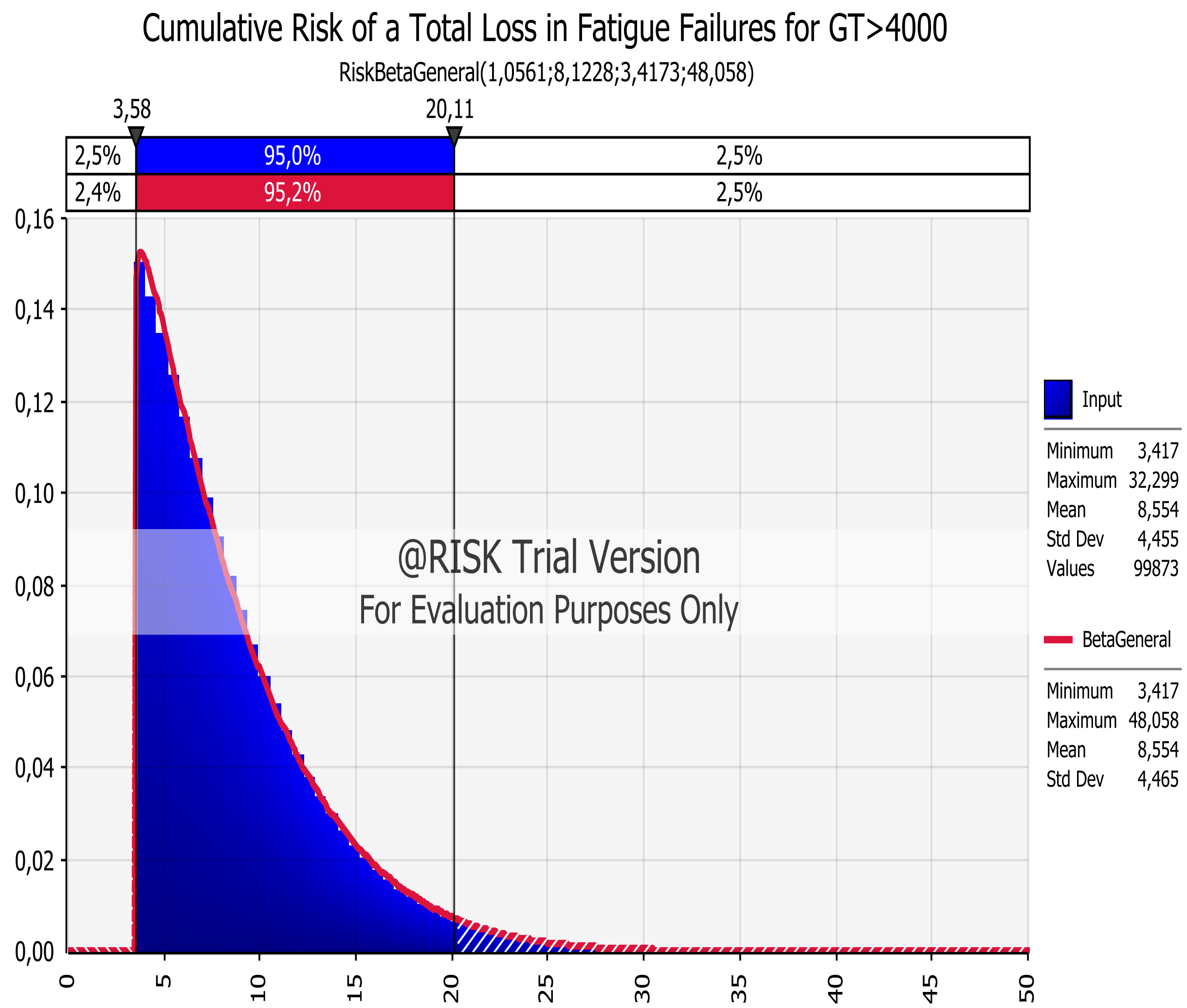


Figure 7.36: Distribution of PDP for a Total Loss of a RoPax> 4,000GT with fatigue failures

By multiplying the outputs of Monte Carlo simulation for the cost of a Refloat with the probability to occur a Refloat in current category (Table 5.5), a variety of values for the cumulative risk in relation to the cost and a distribution were assessed (Figure 7.37).

It is known that mean value of a density probability function is the expected value, so cost’s cumulative risk for curtained category is about 1.058 (Figure 7.37). By Table 5.5, it is derived that from Event Tree analysis emerged that PDP is 0.646 for the existent accidents.

It seems that the theoretical cumulative risk of the cost for a Refloat is higher than the calculated value.

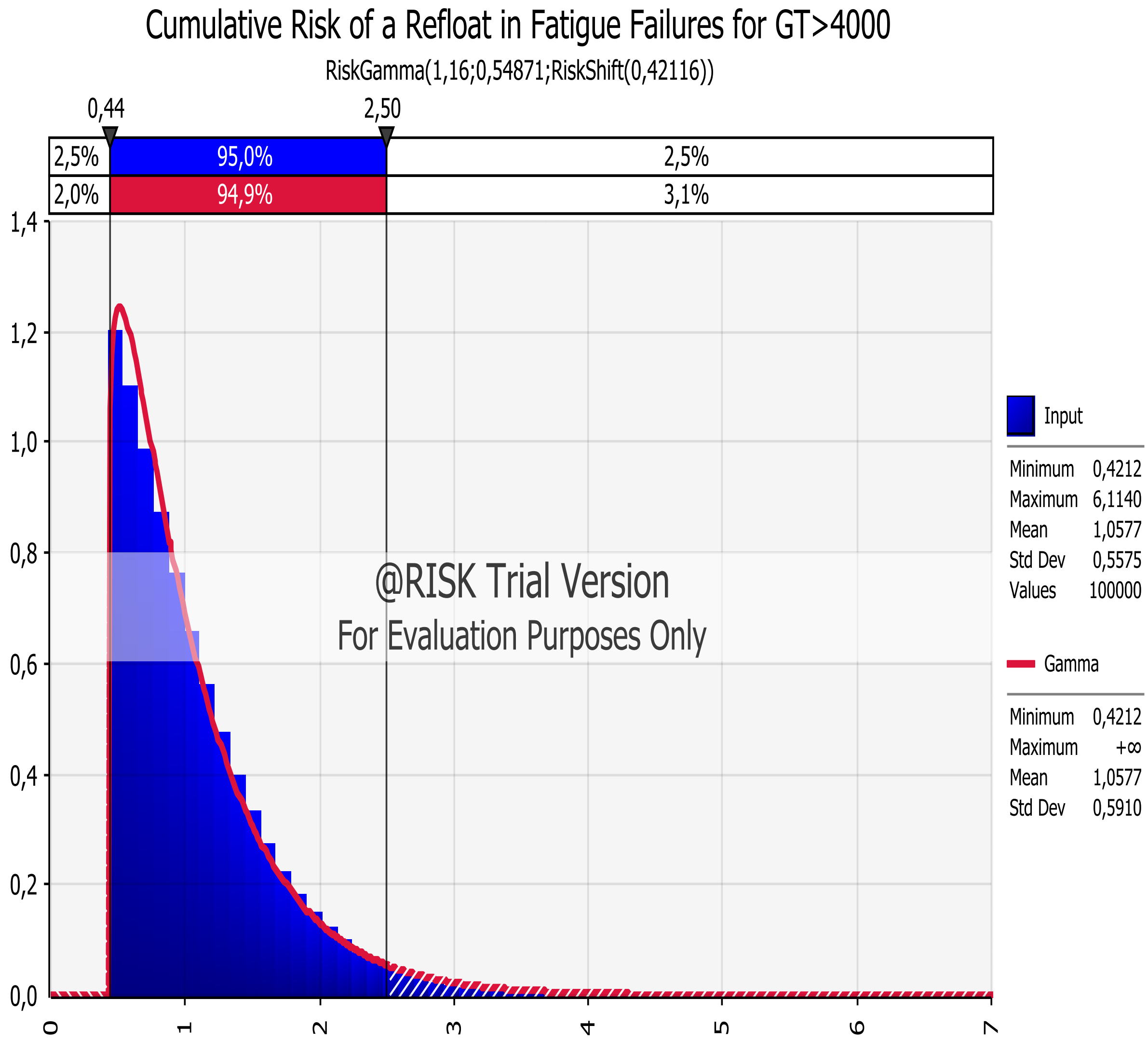


Figure 7.37: Distribution of PDP for a Refloat of a RoPax> 4,000GT with fatigue failures

Another risk contributor that was estimated with the assistance of Monte Carlo simulation and the tool of distribution fitting was cost's cumulative risk for a Scrap. Figure 7.38 indicates that this value is 4.199 in contrast with event tree analysis outcome which was 2.898 (Table 5.5).

The final cumulative risk assessment concerned the total hazard that runs a RoPax ship for GT>4,000 with fatigue failures. For achieving the approach of this value, it was needed to fit a distribution in the correlated outputs of the other PDP of specific category.

As a consequence, Figure 7.39 was formed and the expected cumulative risk for Ships>4,000 GT which would suffer by fatigue failures, found to be 13.807. From the corresponding Event Tree, respective value emerged 10.094 (Table 5.5).

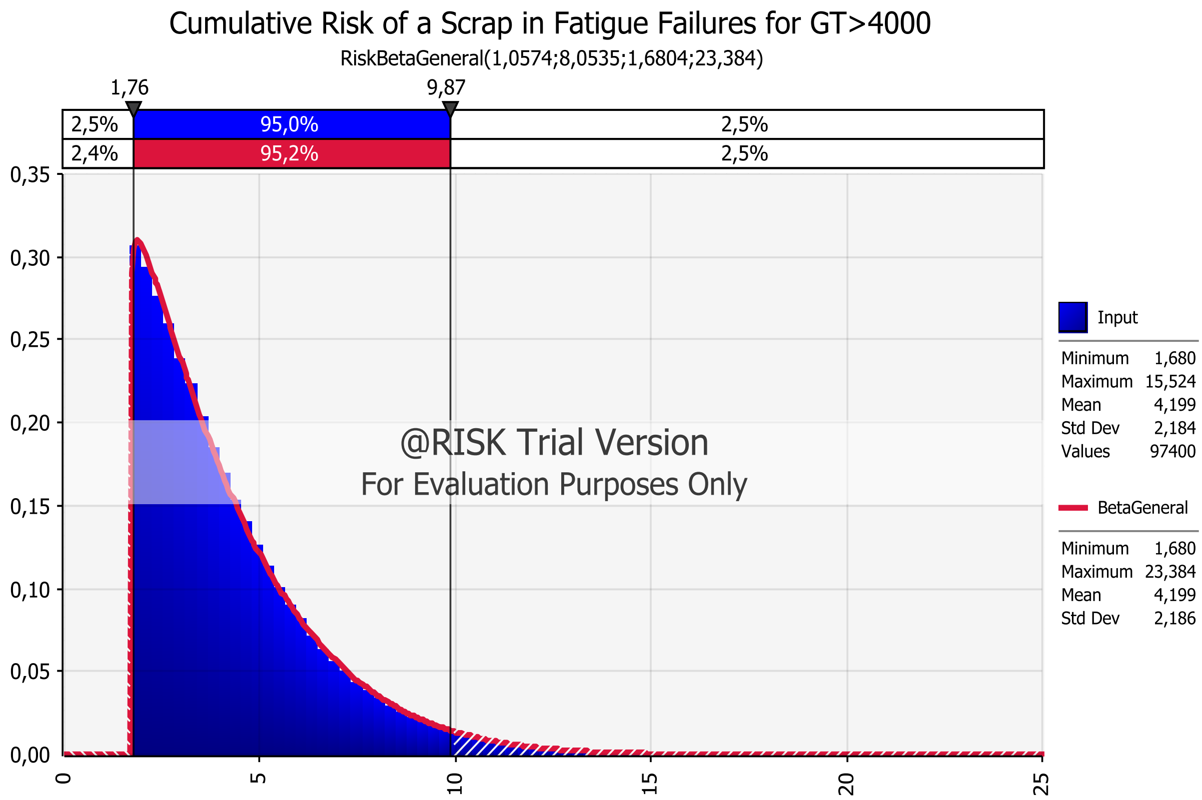


Figure 7.38: Distribution of PDP for a Scrap of a RoPax> 4,000GT with fatigue failures

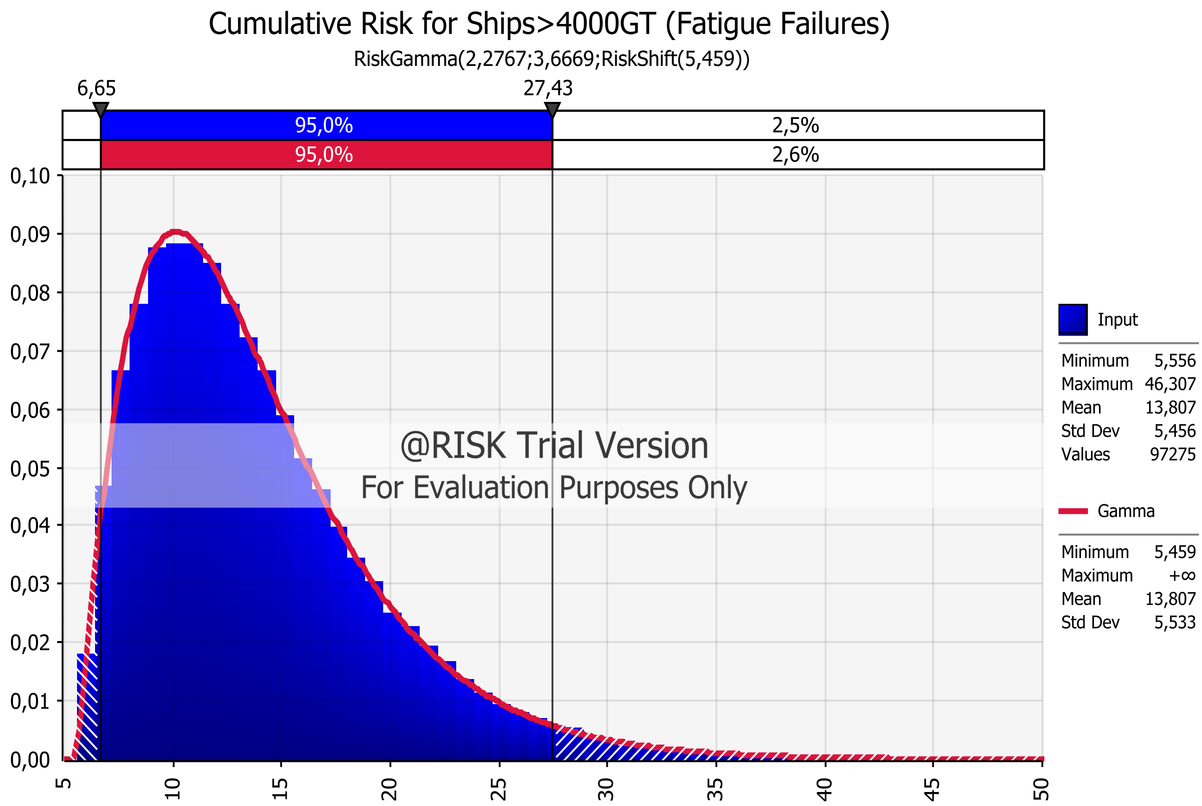


Figure 7.39: Distribution of PDP for RoPax Ships> 4,000GT with fatigue failures

Synoptically, the relation of PDP for the two methods that were used is presented to the Table 7.6.

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	6.550	8.554
Refloat	0.646	1.058
Scrap	2.898	4.199
Total	**10.094**	**13.807**

Table 7.6: Relative Potential Cost for the Large Class with fatigue failures for each approach of analysis

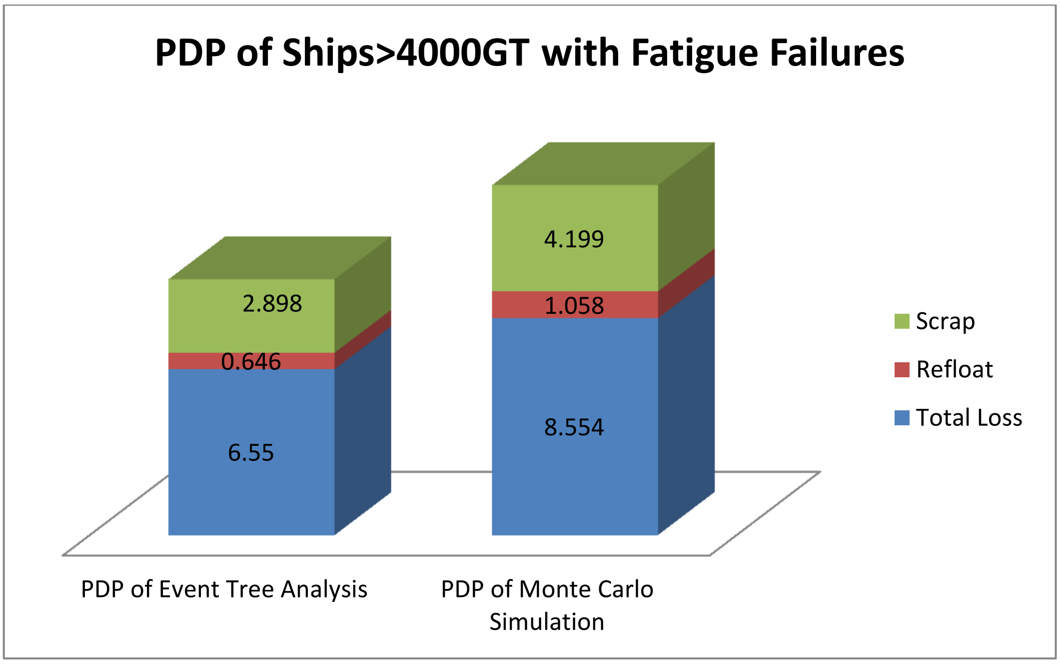


Figure 7.40: Cost's cumulative risks for the Large Class with fatigue failures for each approach of Analysis

7.2.3 Main Analysis with regard to Environmental Impact

The second but not least consequence that selected to be compared and assessed based on whole fleet was the pollution that could emerge after an incident.

RoPax Ships with 4000 GT and below (Small class)

First of all, pollution's distribution for a Total Loss was formed with the aforementioned method (Figure 7.41).

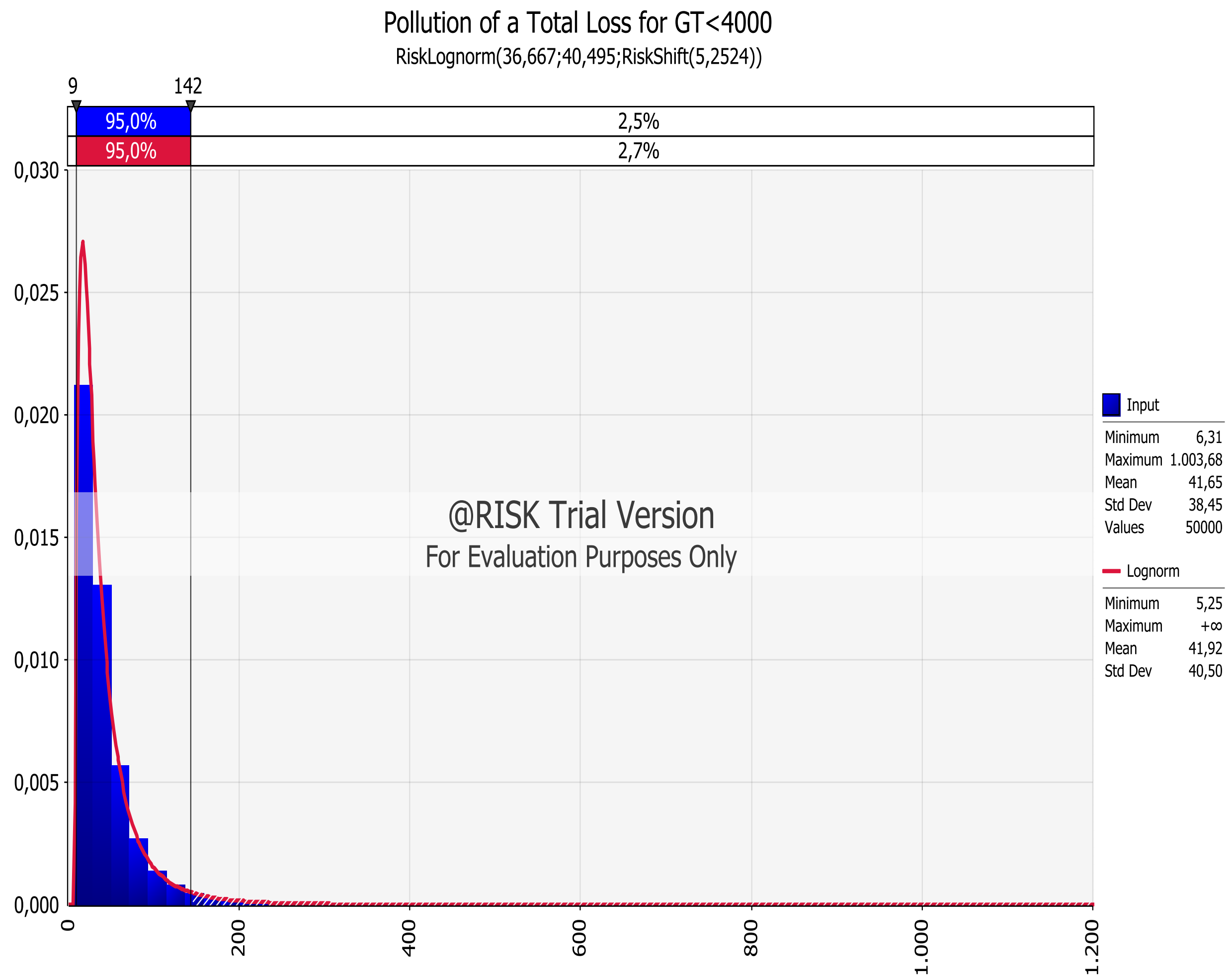


Figure 7.41: Distribution of Pollution in case of Total Loss for RoPax Ships< 4000GT with NASF

Figure 7.41 indicates that for the developed distribution was a Log- Normal distribution with μ= 41.92(mean) and σ=40.5.

By the formation of the distribution that RoPax ships<4,000 GT (Figure 7.42) may result a release of oil in case of a Significant incident, it is established that pollution which is derived by the small class of RoPax ships could 66.9 tonnes of oil, while for a loss of a ship its maximum limit is 1,003.7 tonnes (Figure 7.41).

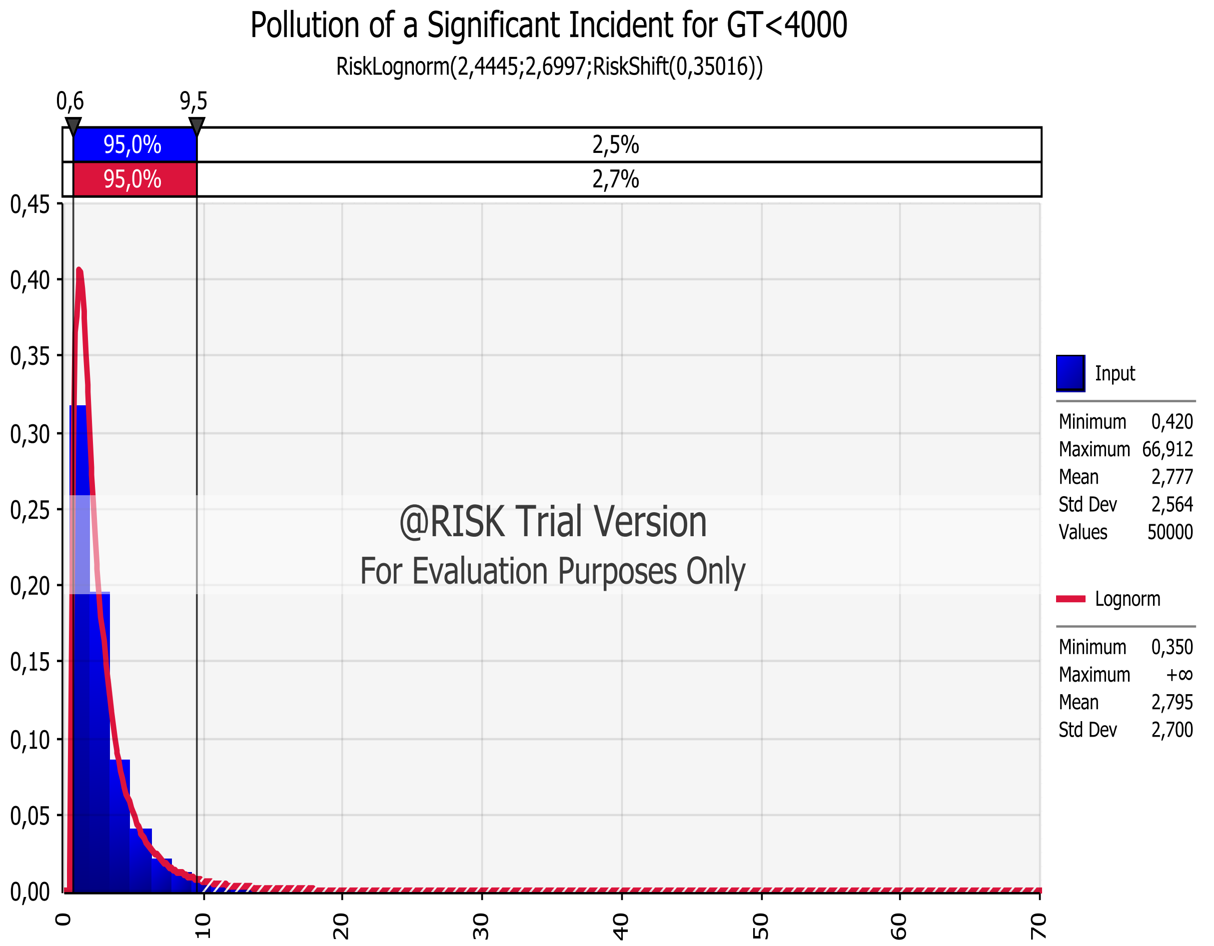


Figure 7.42: Distribution of Pollution in case of a Significant incident for RoPax Ships< 4,000GT with NASF

A first approach of the Potential Environmental Impact (PEI) was to assess relative values for all kind of NASF.

So, distribution's cumulative risk for a Total Loss estimated (Figure 7.43) with having taken into consideration the probability of having pollution after a Total Loss in such class (8.6%) and the potential pollution (Figure 7.41) for this degree of severity.

Figure 7.43 gave us the outcome that the expected value of the PEI is 3.90. On the other hand, the investigation of the reports emerged that current cumulative risk was 3.74, something which means that accident reports of this category led us to accurate results with regard to the pollution in an occasion of a ship's loss.

Similarly, the PEI in case of a Significant incident for Ships<4,000GT was found to be 0.19 by the interpretation of Figure 7.44, whilst concerned cumulative risk calculated by studying the accident reports to be equal to 0.10.

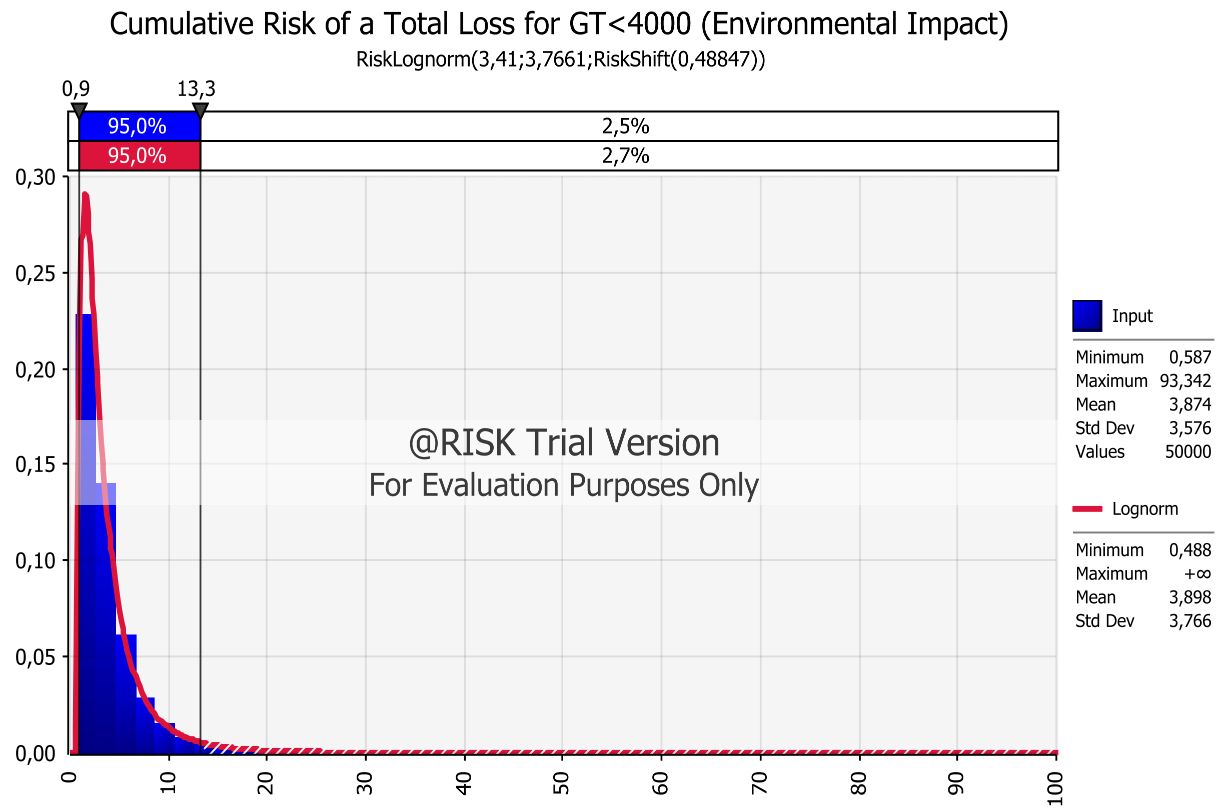


Figure 7.43: Distribution of PEI in case of a Total Loss for RoPax Ships< 4,000GT with NASF

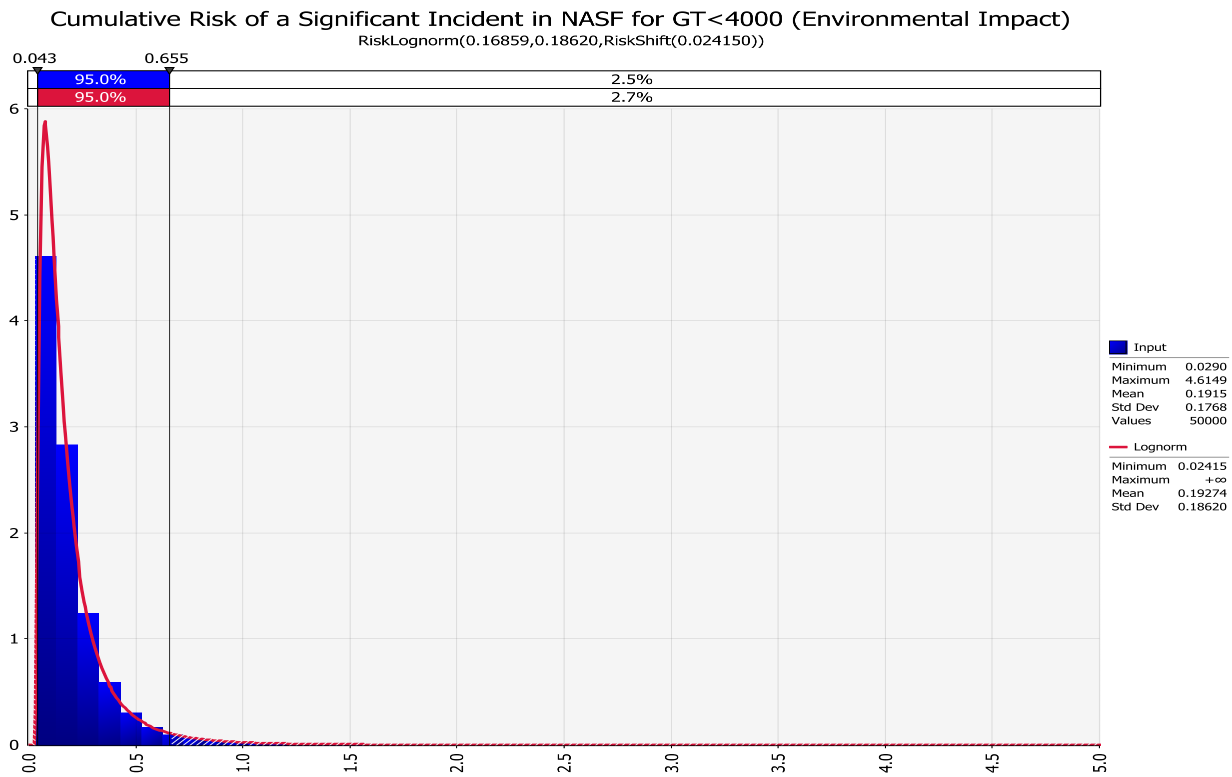


Figure 7.44: Distribution of PEI in case of a Significant incident for RoPax Ships< 4,000GT with NASF

The total cumulative risk of pollution for NASF with taking into account all the fleet independently of casualty's presence on the small class of ships can be arisen by Figure 7.45, as the mean of designed distribution. This value is 4.09, similar to the value of PEI (3.84) which was derived by the given information for the incidents of database.

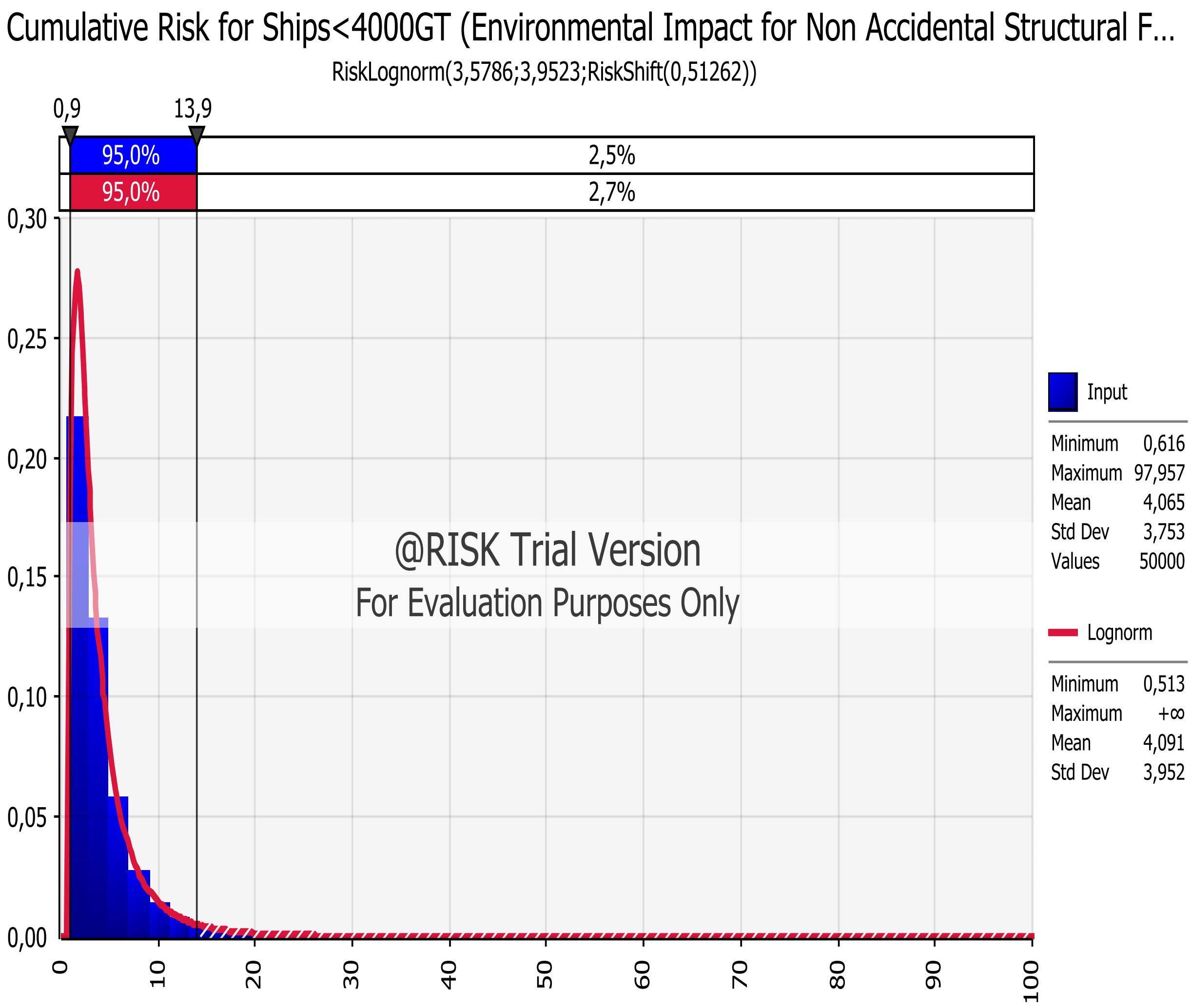


Figure 7.45: Distribution of PEI for RoPax Ships< 4,000GT with NASF

The correlation of the cumulative risks is shown in Table 7.7.

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	3.74	3.90
Significant	0.10	0.19
Total	**3.84**	**4.09**

Table 7.7: Relative Potential Pollution for the Small Class with NASF for each approach of analysis

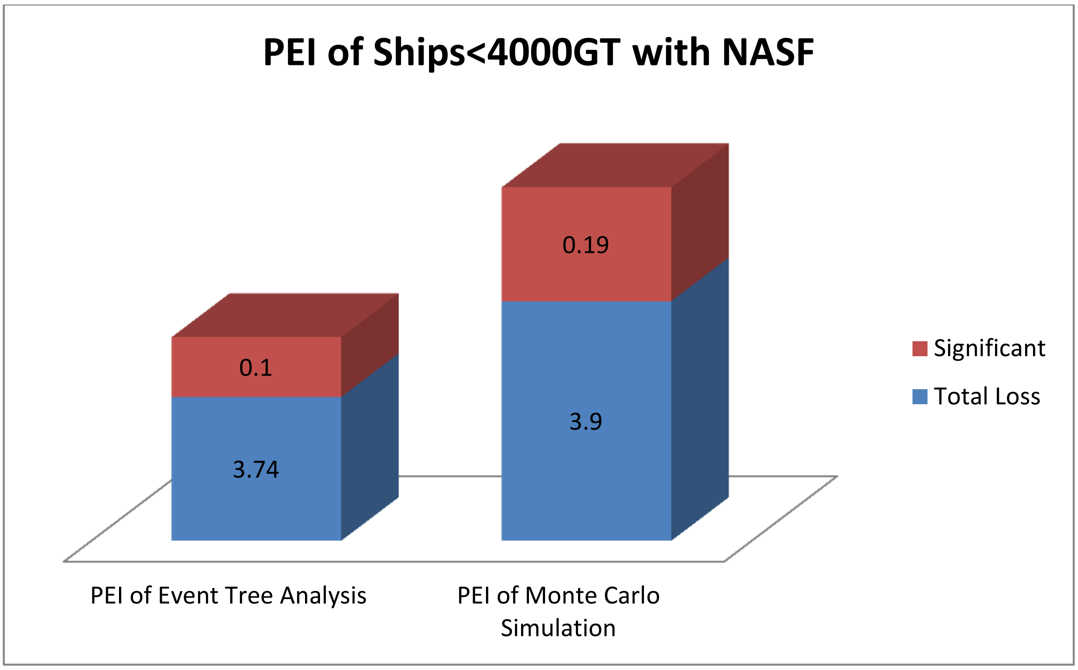


Figure 7.46: Pollution's cumulative risks for the Small Class with NASF for each approach of Analysis

Following the determined methodology of current thesis, cumulative risk with respect to the pollution was also approached by distinguishing NASF to two categories:

- *Small Class with Corrosion*

The risk contributor for the pollution after the loss of a ship was estimated 5.37 (Figure 7.47). Contrary to that, PEI which assessed by Event Tree Analysis was 3.13(Table 5.1). This discrepancy can be justified by the fact that the mean value of the pollution for a Total Loss (Figure 7.41) was 41.92 while oil releases of the accidents in concerned category were lower.

For the opposite reason, PEI for a significant accident calculated from Monte Carlo simulation found to be lower than the cumulative risk of Event Tree Analysis (Table 5.2). But it must be mentioned that value of 0.3 which resulted by Event Tree Analysis is between the boundaries that Figure 7.48 set.

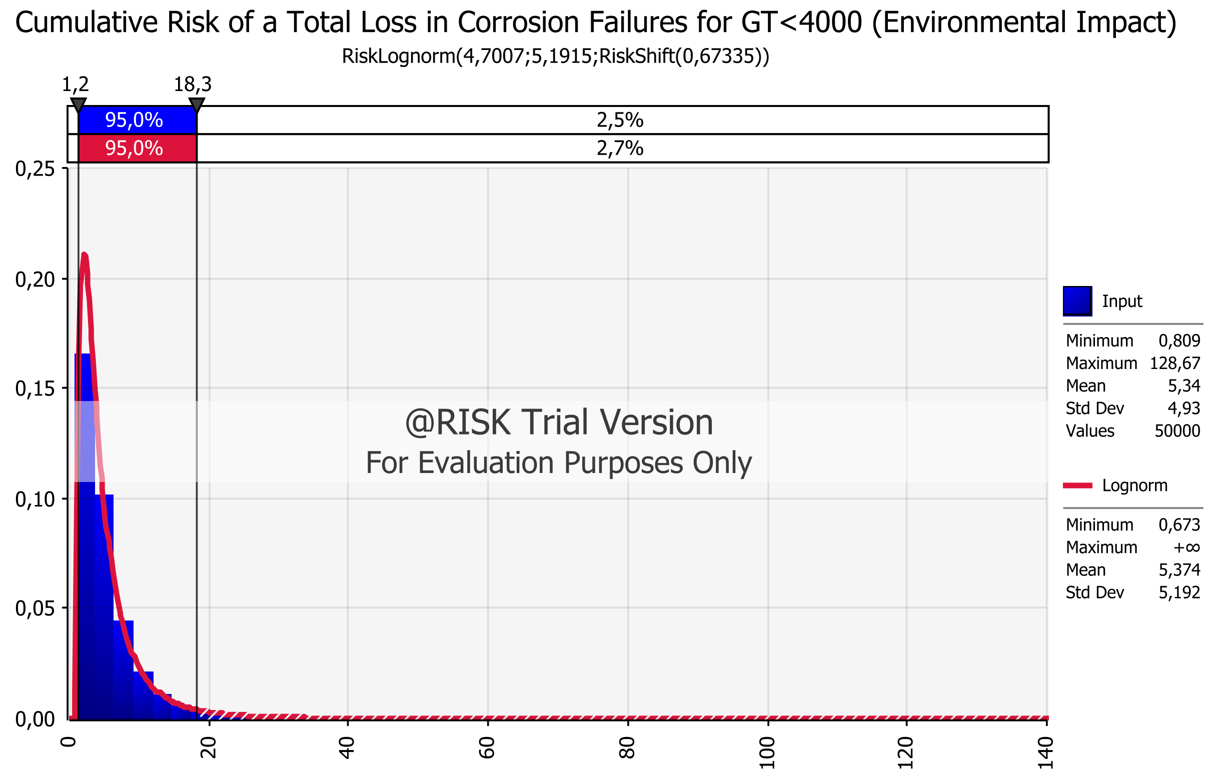


Figure 7.47: PEI in case of a Total Loss for RoPax Ships< 4,000GT with corrosion failures

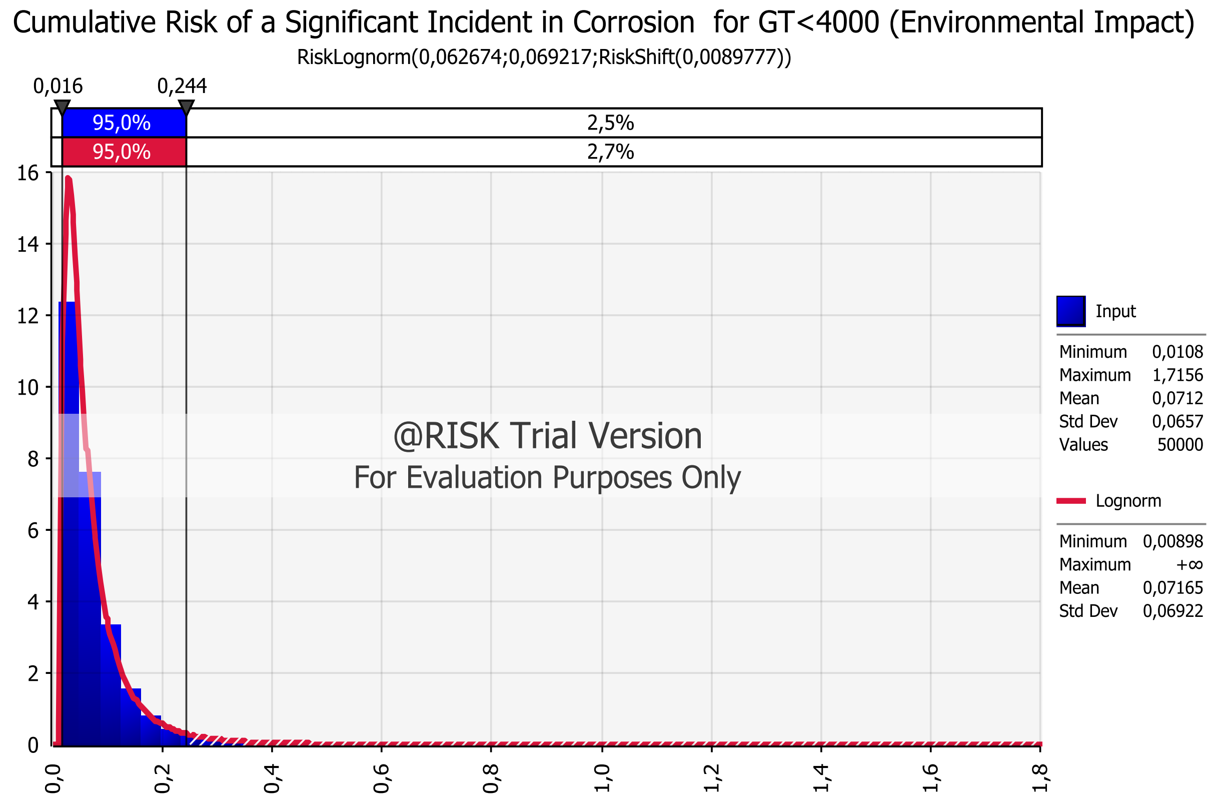


Figure 7.48: PEI in case of a Significant incident for RoPax Ships< 4,000GT with corrosion failures

Having combined the above two risk contributors, it was feasible to find the distribution for the cumulative risk with regards to the pollution for specific category. As a result, cumulative risk found to be approximately 5.45 (Figure 7.49) while it had been estimated before about 3.43.

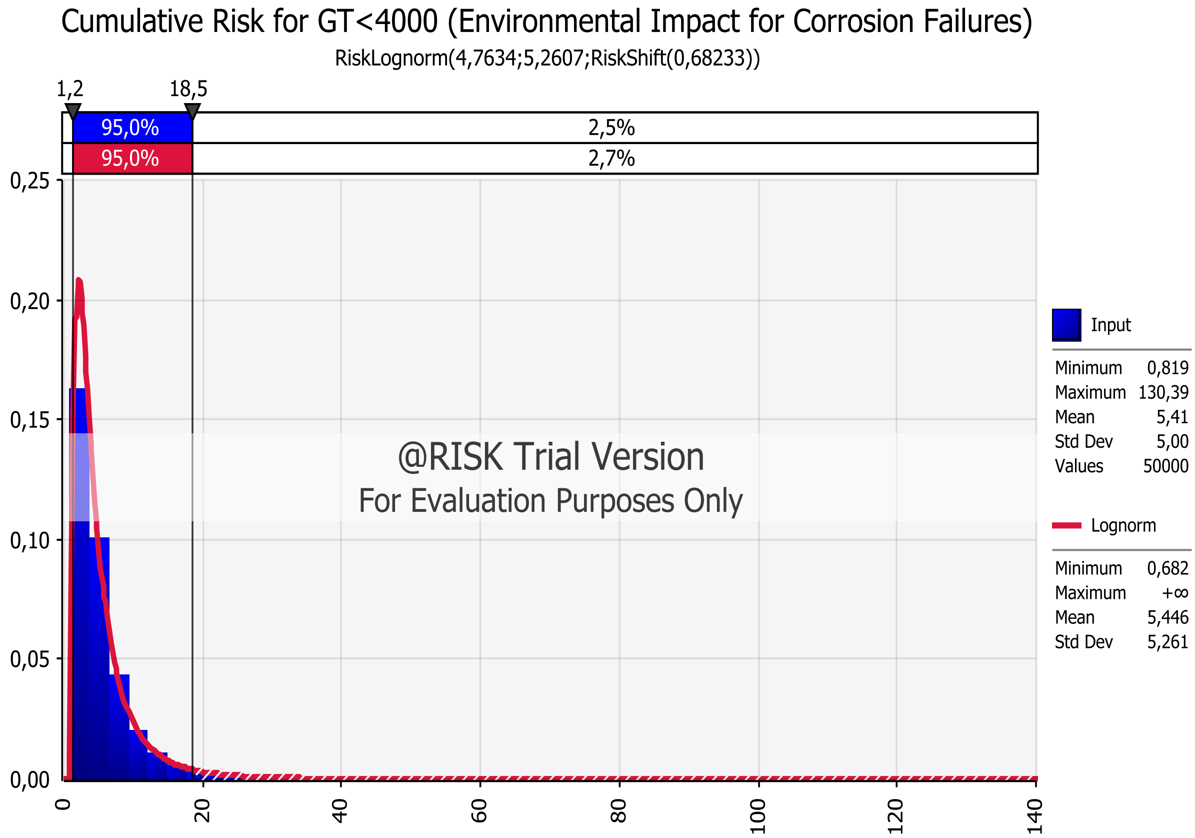


Figure 7.49: PEI for RoPax Ships< 4,000GT with corrosion failures

Event Tree and Monte Carlo simulation's results of the specific category are obvious below:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	3.13	5.37
Significant	0.30	0.07
Total	**3.43**	**5.44**

Table 7.8: Relative Potential Pollution for the Small Class with corrosion failures for each approach of analysis

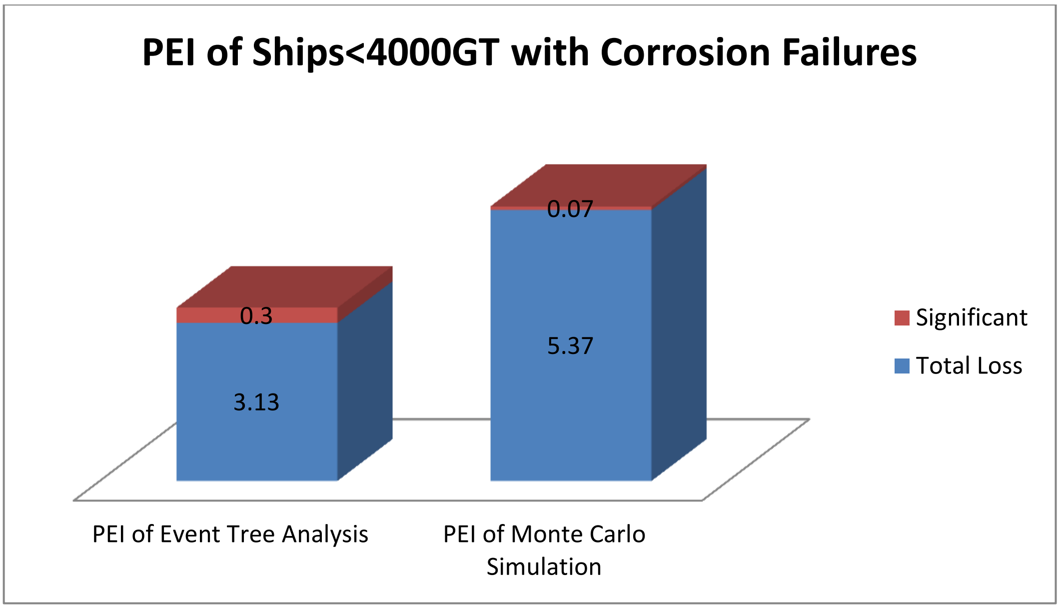


Figure 7.50: Pollution's cumulative risks for the Small Class with Corrosion Failures for each approach of Analysis

- *Small Class with Fatigue Failures*

Distribution of pollution's cumulative risk for a ship due to fatigue failures depends only on the risk contributor for a loss of a ship, as significant incidents accompanied with pollution had not been observed on the investigating data. Consequently, Figure 7.51 gave us the outcome that PEI for the small class with fatigue failure is 5.41.

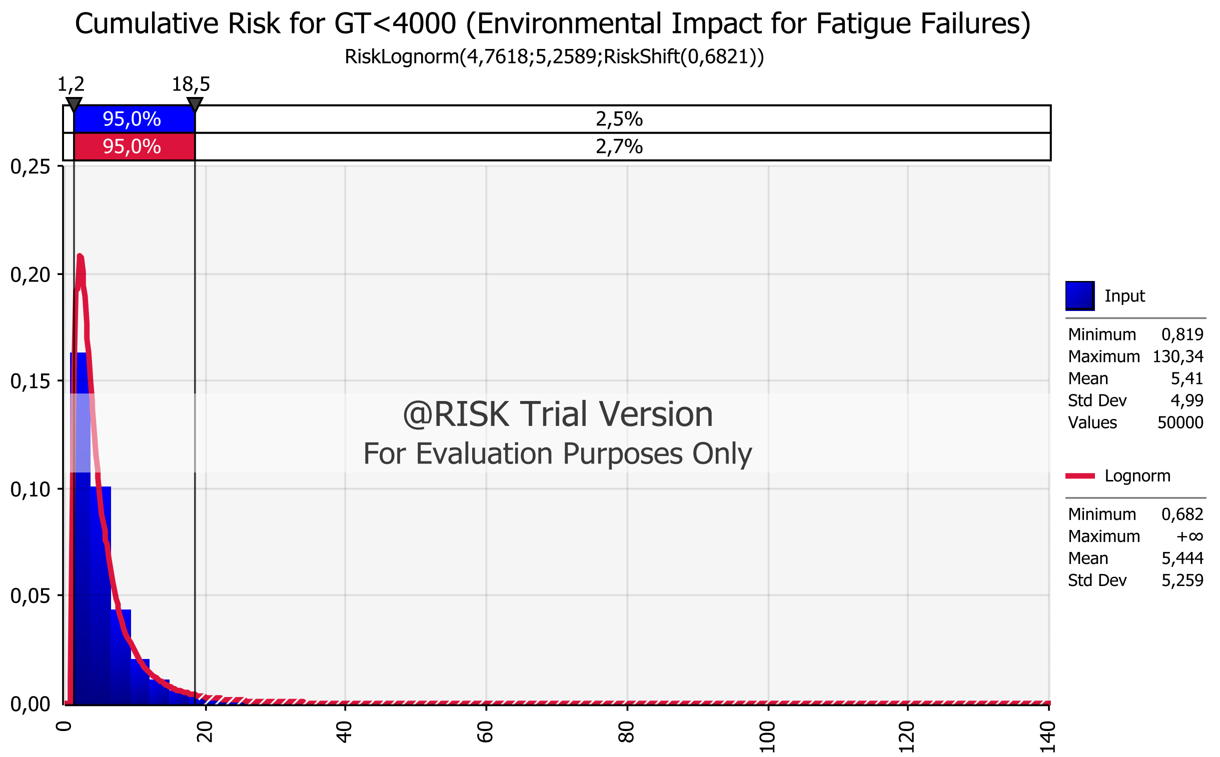


Figure 7.51: PEI for RoPax Ships< 4,000GT with fatigue failures

RoPax Ships with 4000 GT and above (Large class)

It is an undisputed fact that current category's pollution rates differ a lot by those of the small class. It can be noticed that minimum and maximum values of a potential pollution for Total Loss (Figure 7.52) and significant cases (Figure 7.53) are higher than those of small class. An indicative example is that while maximum release of oil could be 1,890.2 tonnes in case of the loss of a ship for RoPax Ships>4,000 GT (Figure 7.52), small class's highest pollution seems to reach the value of 1,003.7tonnes (Figure 7.41).

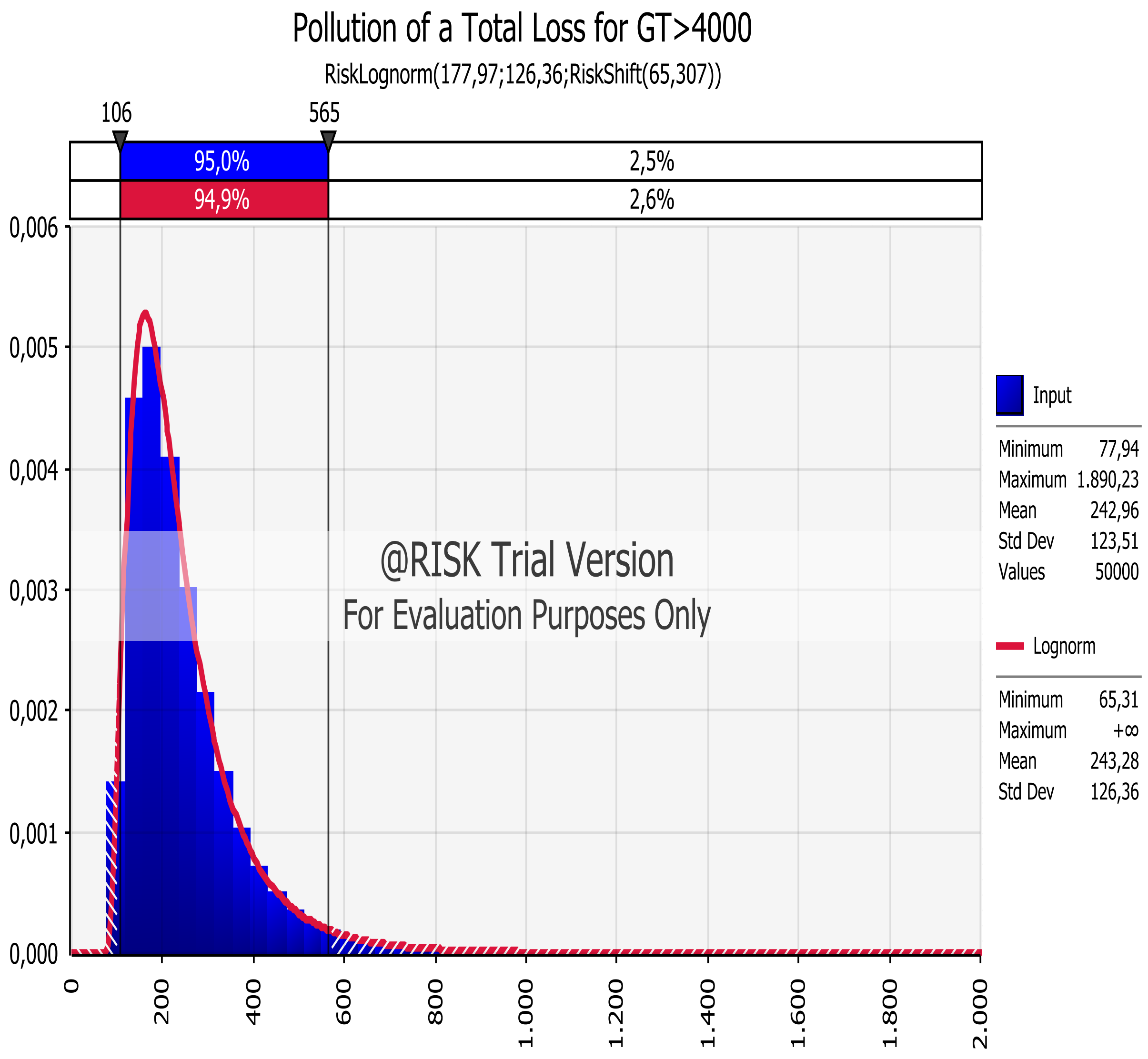


Figure 7.52: Distribution of the pollution in case of a Total Loss for RoPax Ships> 4,000GT

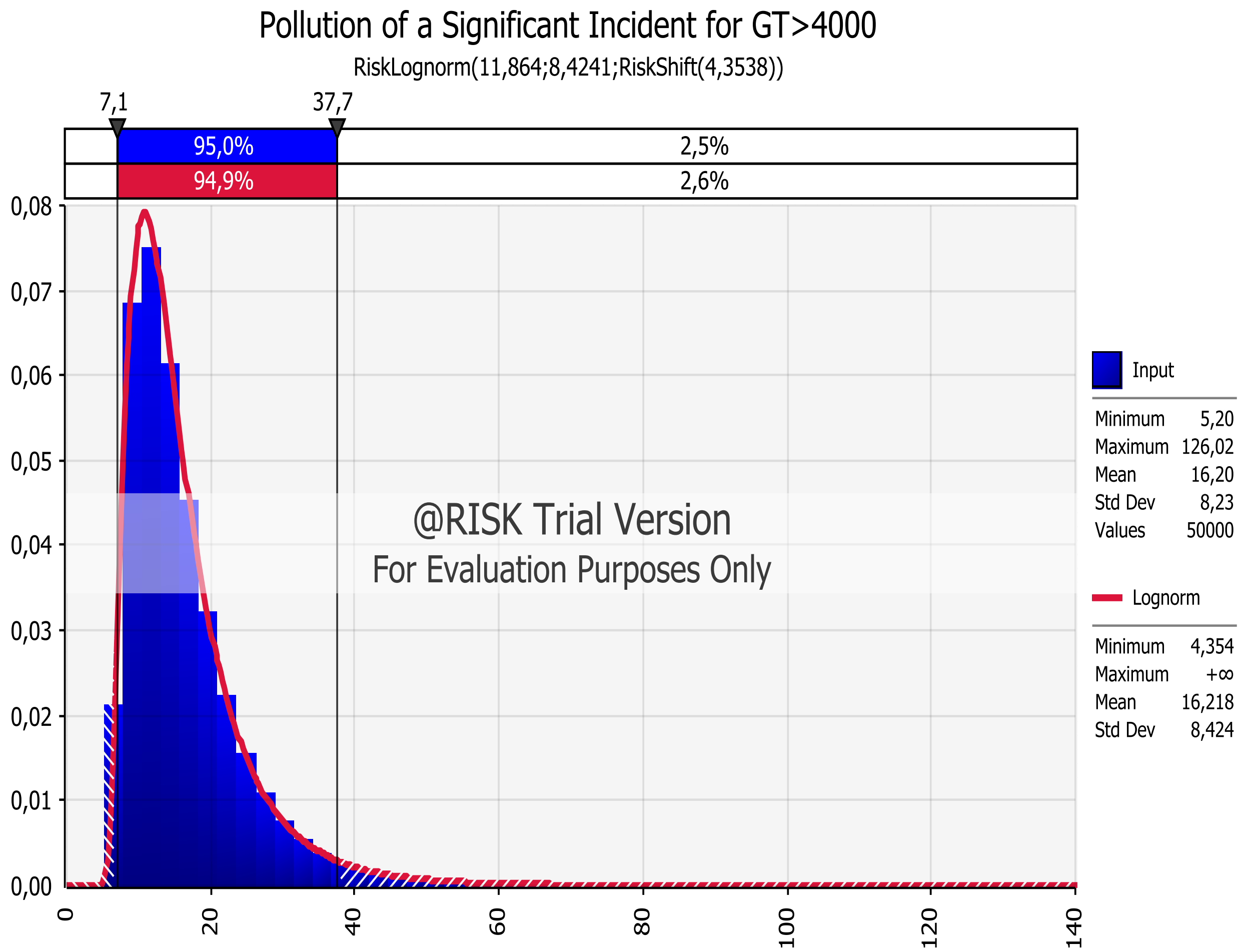


Figure 7.53: Distribution of the pollution in case of a Significant incident for RoPax Ships> 4000GT

After the definition that pollution's distributions follow the Log-Normal Distribution, it was easy to create the distributions for the predefined cumulative risks. Knowing the probabilities of occurring pollution after the loss of a ship (4.76%) and after a significant casualty, cumulative risks for these two occasions with respect to the pollution were feasible to be figured.

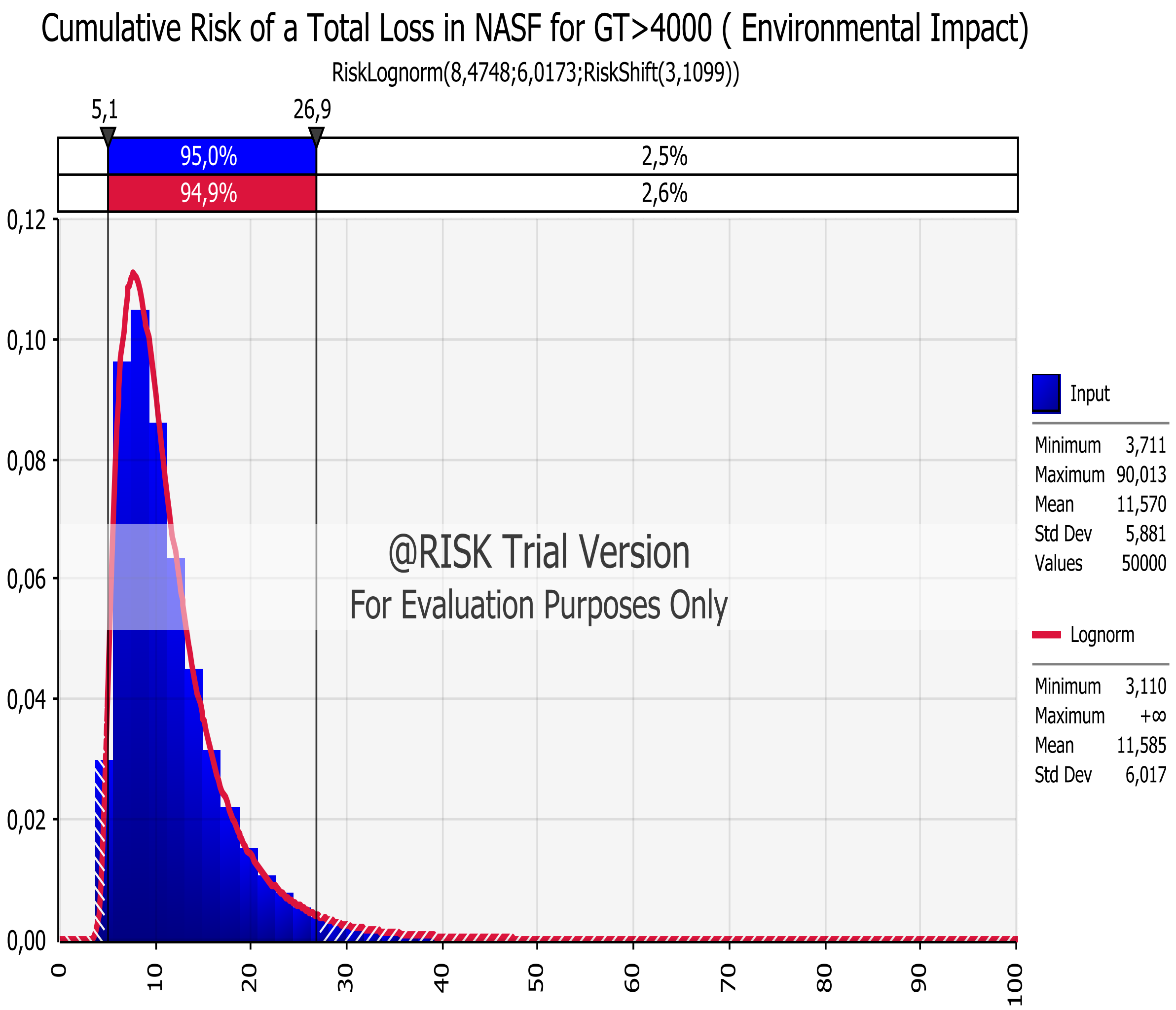


Figure 7.54: Distribution of the PEI in case of a Total Loss for RoPax Ships> 4,000GT with NASF

Cumulative risk for Total Loss cases is about 11.59 (Figure 7.54) and for Significant incidents was 4.06 (Figure 7.55). These values are quite different than those that characterize the examined accident reports, which was for the former 4.99 and the latter 0.17.

Large class of RoPax vessels has the cumulative risk of 15.64 as far as pollution is concerned (Figure 7.56).

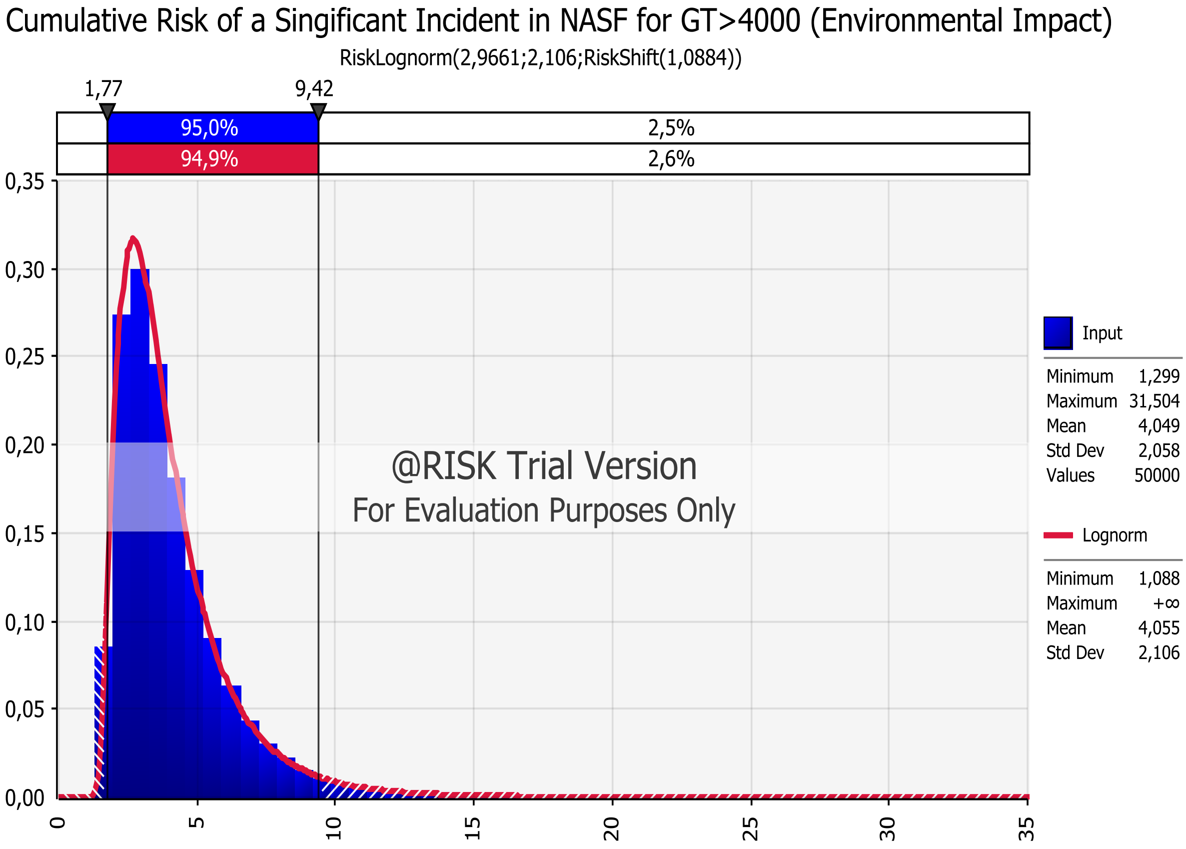


Figure 7.55: Distribution of the PEI in case of a Significant Incident for RoPax Ships> 4,000GT with NASF

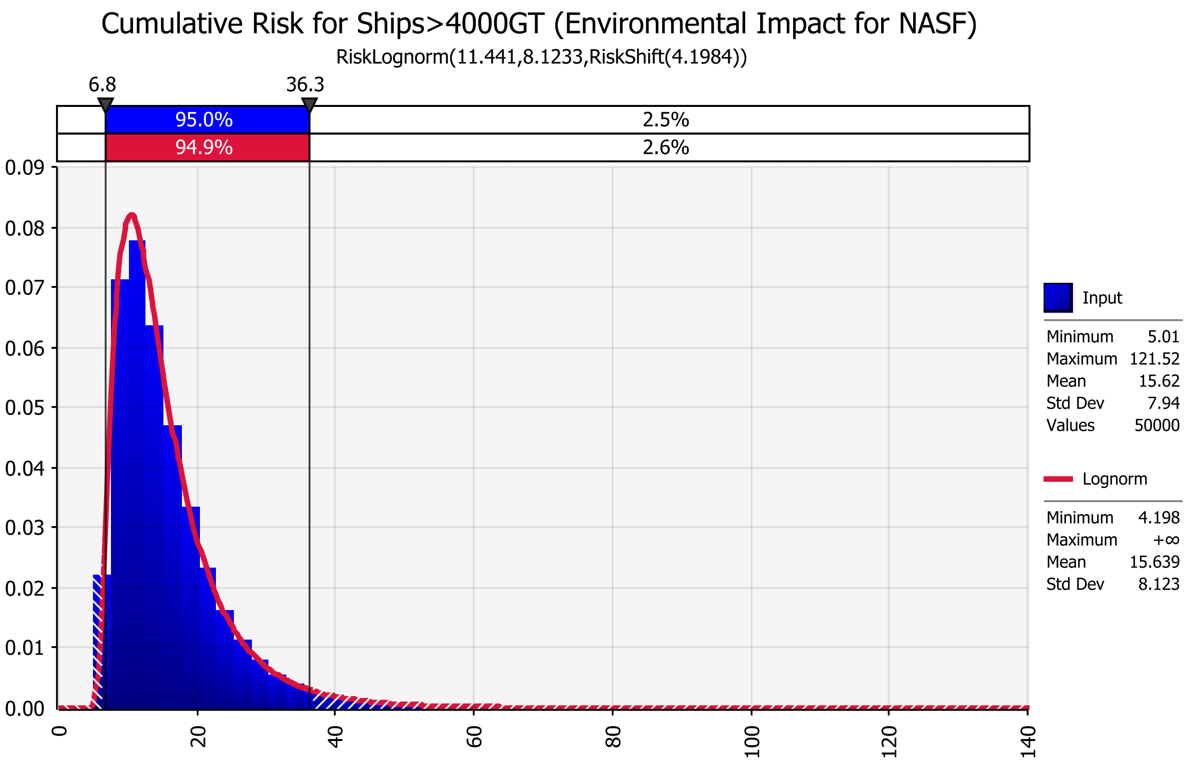


Figure 7.56: Distribution of the PEI for RoPax Ships> 4,000GT with NASF

A brief comparison between the results for specific category can be seen below:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	4.99	11.58
Significant	0.17	4.06
Total	**5.16**	**15.64**

Table 7.9: Relative Potential Pollution for the Large Class with NASF for each approach of analysis

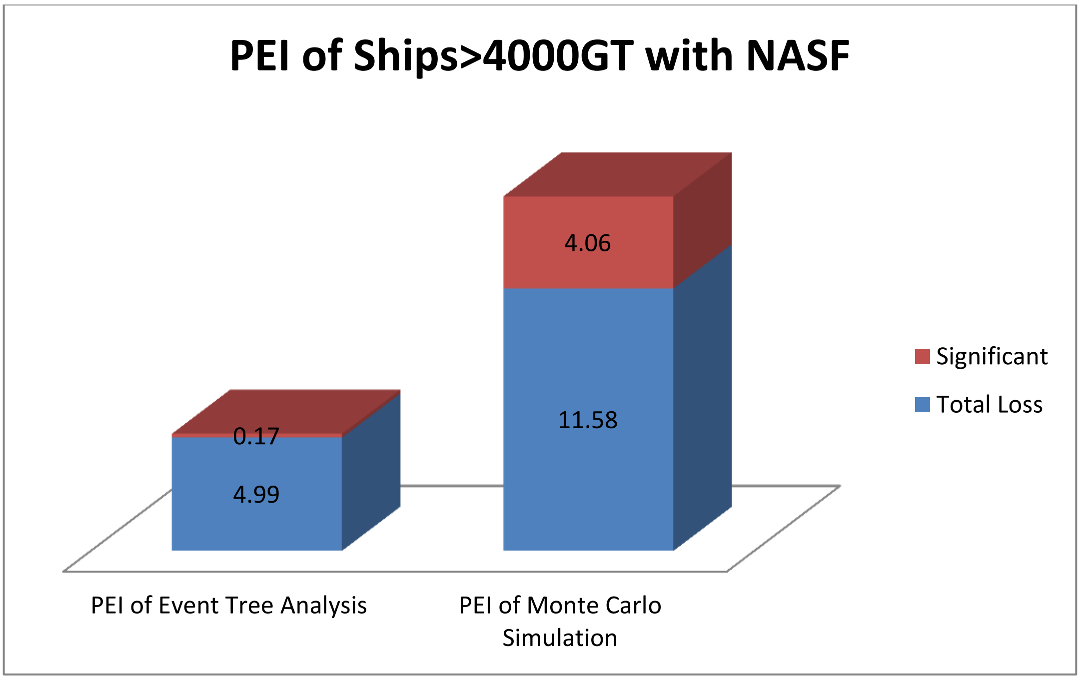


Figure 7.57: Pollution's cumulative risks for the Large Class with NASF for each approach of Analysis

Furthermore, cumulative risk's contributions for pollution rates estimated for the two categories which are listed below:

- *Large Class with Corrosion*

Event Tree analysis led us to the conclusions that cumulative risk of pollution was 4.02 in an occasion of the loss of a ship and 0.2 for incidents that identified as significant. These two values are contained in the potential values that a cumulative risk could have for each degree of severity and it can be comprehended below.

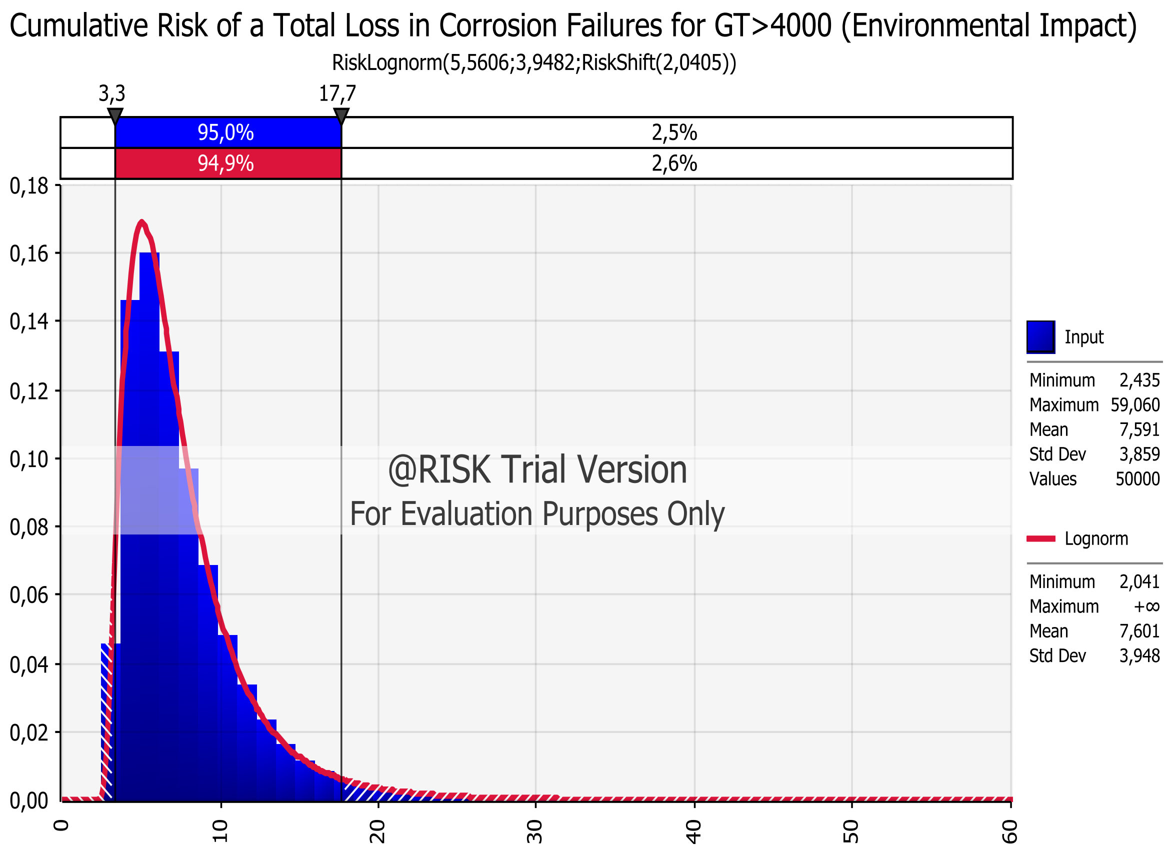


Figure 7.58: Distribution of the PEI of a Total Loss for RoPax Ships> 4,000GT with corrosion failures

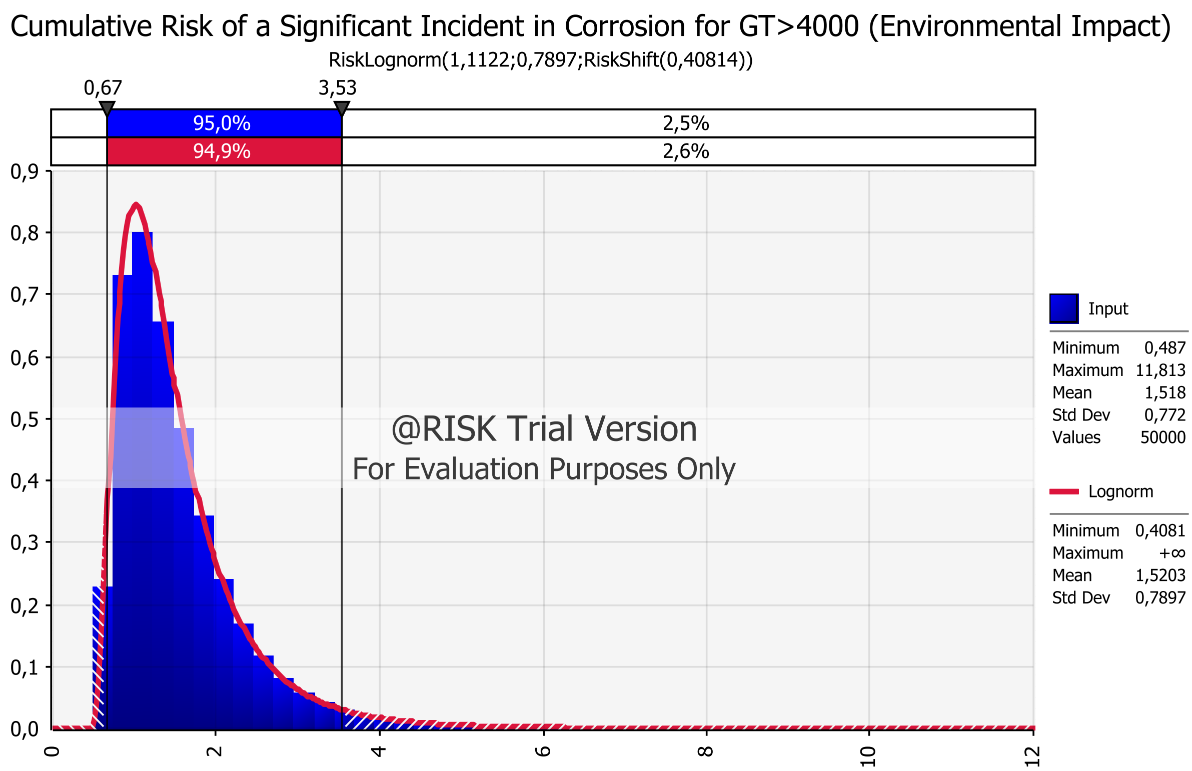


Figure 7.59: PEI of a Significant incident for RoPax Ships> 4,000GT with corrosion failures

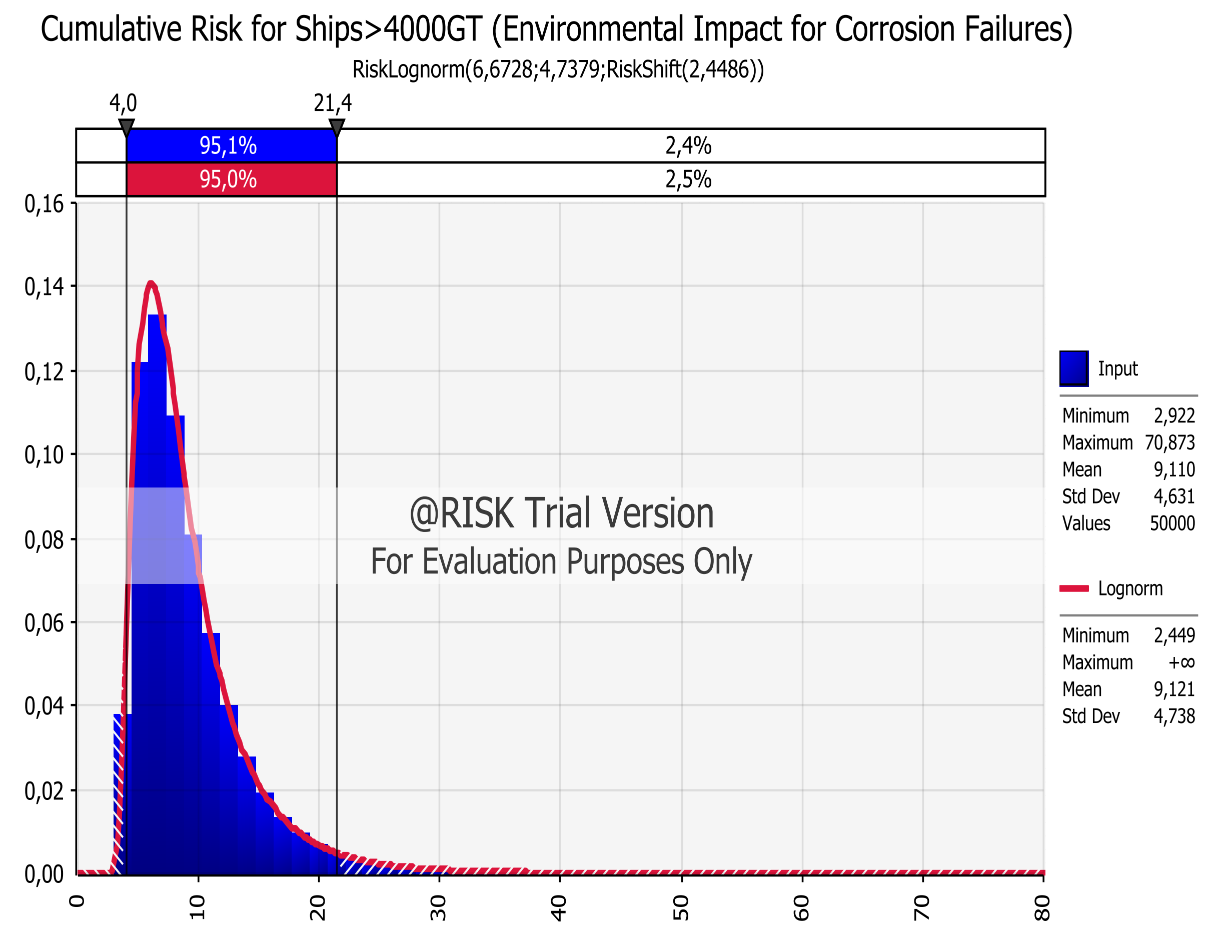


Figure 7.60: Distribution of the PEI for RoPax Ships> 4,000GT with corrosion failures

Cumulative Risk's distribution for RoPax ships that belong to large class with corrosion failures follow the Log-Normal distribution with μ=9.121(expected value of the PEI) and σ=4.738.

Therefore, for the large class with fatigue failures, cumulative risks with respect to the pollution for both species of analysis (Event Tree and Monte Carlo simulation Analysis) are:

Degree of Severity	Cumulative Risk estimated in Event Tree Analysis	Cumulative Risk assessed with Monte Carlo Simulation
Total Loss	4.02	7.60
Significant	0.20	1.52
Total	**4.22**	**9.12**

Table 7.10: Relative Potential Pollution for the Large Class with NASF failures for each approach of analysis

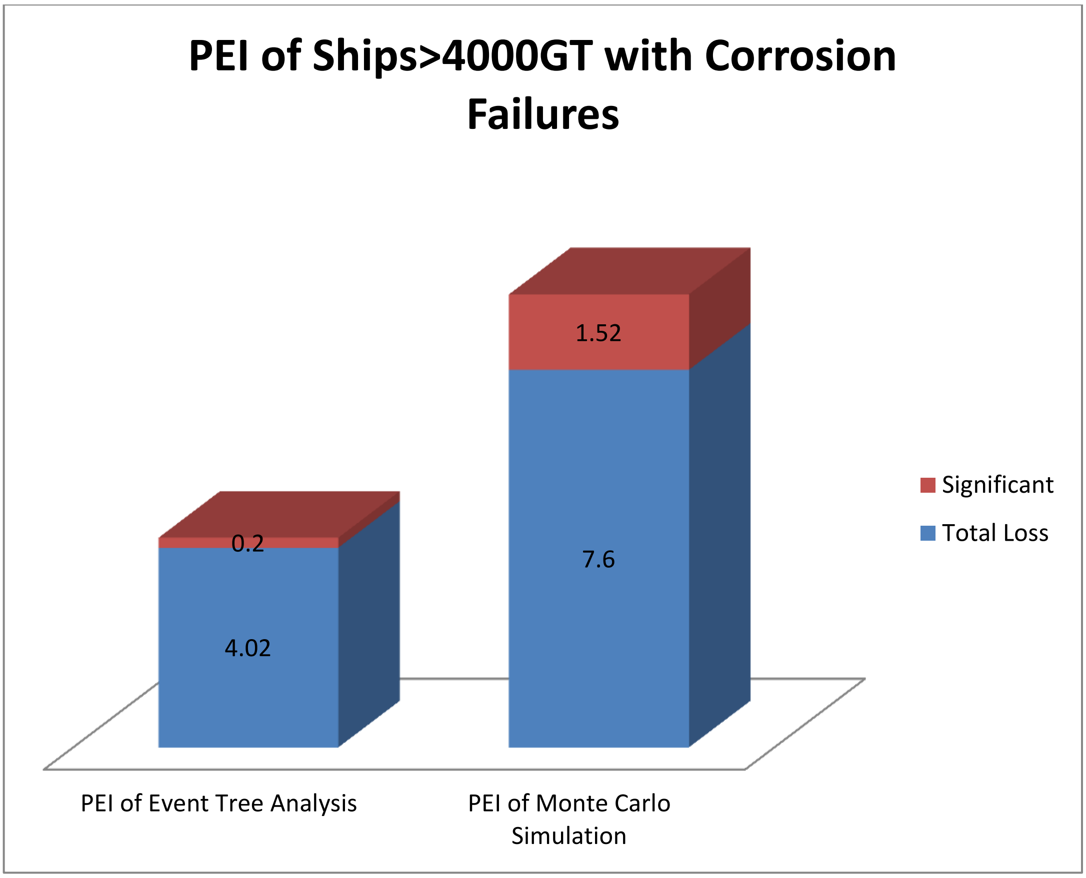


Figure 7.61: Pollution's cumulative risks for the Large Class with Corrosion failures for each approach of Analysis

- *Large Class with Fatigue Failures*

By recalling the outcomes of Event Tree Analysis for specific category (Table 5.4), which were derived by the existent accidents, it can be noticed by Figure 7.62, Figure 7.62 and Figure 7.63 that theoretical values of relative cumulative risks are much higher than the previous results of Risk Analysis.

As a matter of fact, the differences between these values are absolutely reasonable because of the differences between the pollution that occurred in reality and was observed in a few circumstances, and the possible pollution which could be caused.

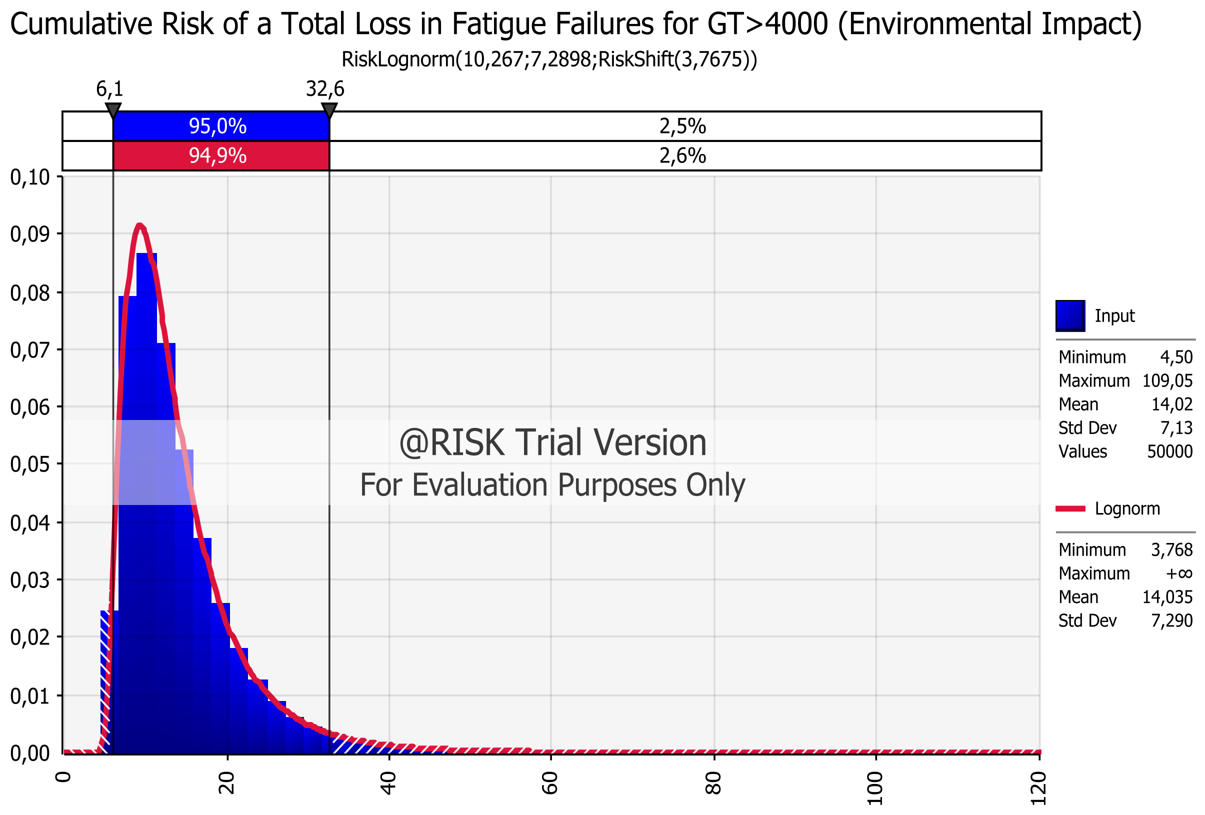


Figure 7.62: Distribution of the PEI of a Total Loss for RoPax Ships> 4,000GT with fatigue failures

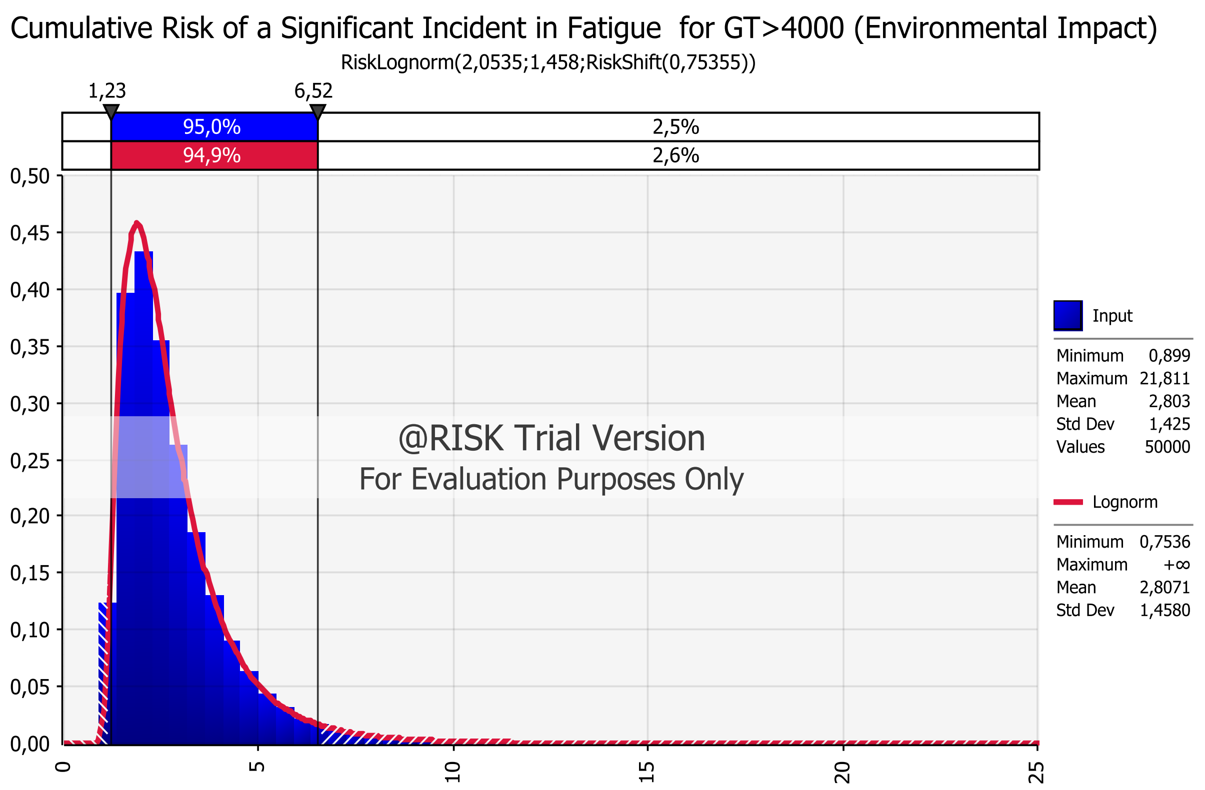


Figure 7.63: PEI of a Significant Incident for RoPax Ships> 4,000GT with fatigue failures

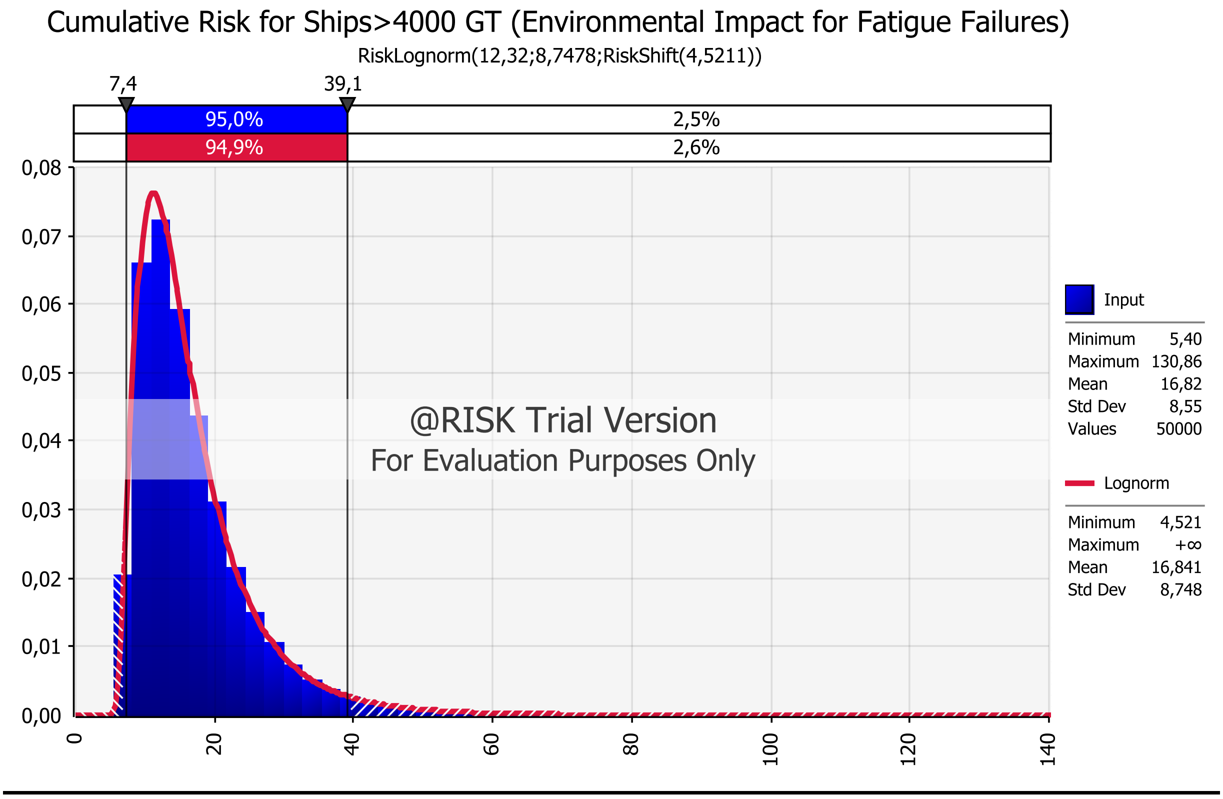


Figure 7.64: Distribution of the PEI for RoPax Ships> 4,000GT with fatigue failures

The connection of Risk Analysis and Monte Carlo simulation‘s outcomes is presented on the Table 7.11.

Degree of Severity	**Cumulative Risk estimated in Event Tree Analysis**	**Cumulative Risk assessed with Monte Carlo Simulation**
Total Loss	4.44	14.03
Significant	0.14	2.81
Total	**4.58**	**16.84**

Table 7.11: Relative Potential Pollution for the Large Class with fatigue failures for each approach of analysis

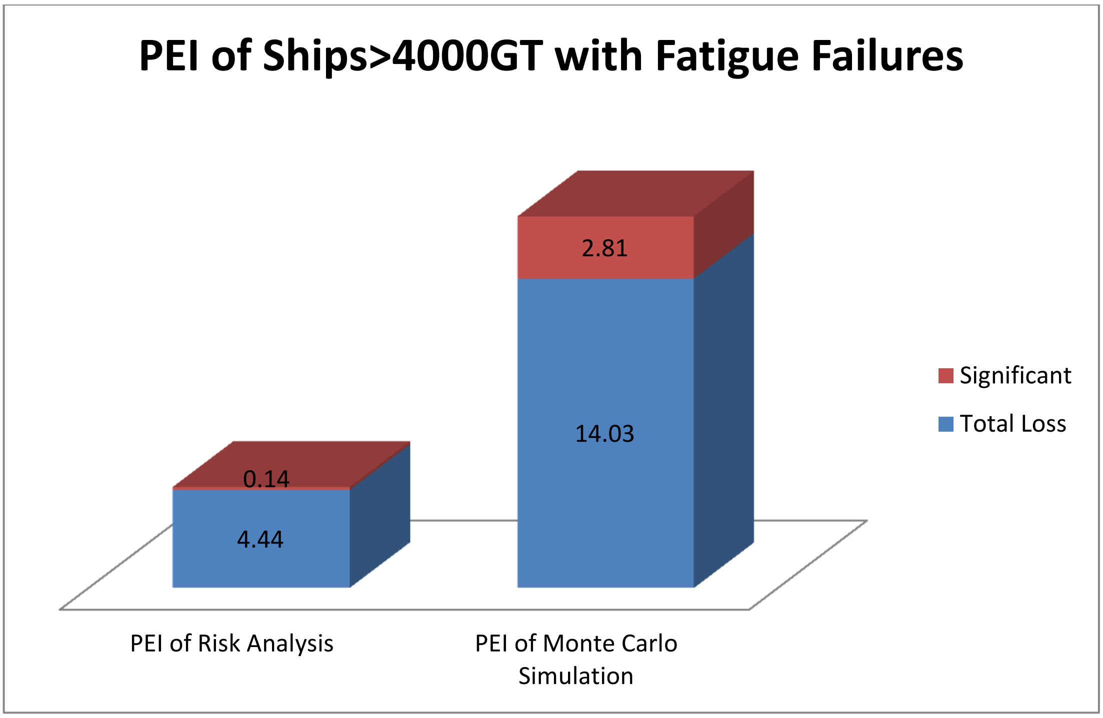


Figure 7.65: Pollution's cumulative risks for the Large Class with Fatigue failures for each approach of Analysis

7.2.4 Results of Distributions

For the better comprehension of the behavior of each distribution, data of the emerged distributions are presented below aggregately.

Initially, characteristics of the GT, LS and GT*Speed distributions are obvious below:

	Initial Failure	Gross Tonnage(GT)		Lightship(LS)		GT*Speed	
Small Class	Fatigue	Triangular	a=200	Gamma	k=1.1276	Log-Normal	μ=19,618.4
	Corrosion		b=4,470.2		θ=1,122.7		σ=32,847.6
			c=1,623.4				
Large Class	Fatigue	Exponential	σ=9971.3	Log-Normal	μ=11,268.3	Log-Normal	μ=220,890.9
	Corrosion		min.=4,002.1		σ=7,570.6		σ=180,950

Table 7.12: Table related to the distributions of the Preliminary Analysis

Table 7.13 shows the characteristics of the costs distributions for each degree of Severity and class.

	Initial Failure	Damage To Property					
Degree of Severity		Total Loss		Refloat		Scrap	
Small Class	Fatigue	Beta	α=1.1512	Beta	α=1.1512	Beta	α=1.1264
	Corrosion		β=1.8461		β=1.8461		β=1.7544
			min=4.462		min=1.155		min=4.419
	NASF		max=44.241		max=11.060		max=43.209
Large Class	Fatigue	Beta	α=1.0561	Beta	α=1.0744	Beta	α=1.0574
	Corrosion		β=8.1229		β=10.655		β=8.0535
			min=44.38		min=11.085		min=44.22
	NASF		max=624.13		max=193.85		max=615.37

Table 7.13: Table related to the distributions of the Main Analysis with respect to Property to Damage

Furthermore, distributions for the cumulative risk with respect to Damage to Property for each class and Degree of Severity are represented in Table 7.14.

	Initial Failure	Cumulative Risk with respect to Damage to Property					
Degree of Severity		Total Loss		Refloat		Scrap	
Small Class	Fatigue	Beta	α=1.1512 β=1.8461 min=1.1008 max=10.9142	N/A	N/A	Beta	α=1.1263 β=1.754 min=0.1149 max=1.1234
	Corrosion	Beta	α=1.1512 β=1.8461 min=0.9148 max=9.0693	Beta	α=1.1512 β=1.8461 min=0.0286 max=0.2831	Beta	α=1.1263 β=1.754 min=0.1131 max=1.1061
	NASF	Beta	α=1.1512 β=1.8461 min=4.443 max=9.954	Beta	α=1.1512 β=1.8461 min=0.0096 max=0.0953	Beta	α=1.1263 β=1.754 min=0.1143 max=1.1147
Large Class	Fatigue	Beta	α=1.0561 β=8.1228 min=3.417 max=48.058	Gamma	α=1.16 β=0.5487	Beta	α=1.0574 β=8.0535 min=1.680 max=15.524
	Corrosion	Beta	α=1.0561 β=8.1228 min=2.796 max=39.320	Beta	α=1.0744 β=10.655 min=0.3436 max=6.0093	N/A	
	NASF	Beta	α=1.0561 β=8.1228 min=3.1701 max=44.582	Beta	α=1.0744 β=10.655 min=0.3960 max=6.9243	Beta	α=1.0574 β=8.0535 min=0.8424 max=11.723

Table 7.14: Table related to the distributions of the Main Analysis with respect to Property to Damage

In addition, cumulative risk distributions without concerning the Degree of Severity are obvious to the continuation of study (Table 7.15).

	Initial Failure	**Cumulative Risk with respect to Damage to Property**	
Degree of Severity		Overall	
Small Class	Fatigue	Beta	α=1.2047
			β=1.8747
			min=1.218
			max=11.964
	Corrosion	Beta	α=1.2035
			β=1.8722
			min=1.0582
			max=10.3943
	NASF	Beta	α=1.2041
			β=1.8733
			min=1.1298
			max=11.0986
Large Class	Fatigue	Gamma	α=2.2767
			β=3.6669
	Corrosion	Beta	α=1.0561
			β=8.1228
			min=3.140
			max=44.157
	NASF	Gamma	α=1.895
			β=3.4831

Table 7.15: Table related to the distributions of the Main Analysis with respect to Property to Damage

Moreover, distributions' features according to the pollution (Table 7.16) and the cumulative risk of environmental impact (7.17) are shown below:

	Initial Failure	Pollution			
Degree of Severity		Significant		Total Loss	
Small Class	Fatigue	Log-Normal	μ=2.795	Log-Normal	μ=41.92
	Corrosion		σ=2.700		σ=40.50
	NASF				
Large Class	Fatigue	Log-Normal	μ=16.218	Log-Normal	μ=243.28
	Corrosion		σ=8.424		σ=126.36
	NASF				

Table 7.16: Table related to the distributions of the Main Analysis with respect to Environmental Impact

	Initial Failure	Cumulative Risk with respect to Environmental Impact					
Degree of Severity		Significant		Total Loss		Overall	
Small Class	Fatigue	N/A	N/A	Log-Normal	μ=5.444 σ=5.259	Log-Normal	μ=5.444 σ=5.259
	Corrosion	Log-Normal	μ=0.072 σ=0.069	Log-Normal	μ=5.374 σ=5.192	Log-Normal	μ=5.446 σ=5.261
	NASF	Log-Normal	μ=0.193 σ=0.186	Log-Normal	μ=3.898 σ=3.766	Log-Normal	μ=4.091 σ=3.952
Large Class	Fatigue	Log-Normal	μ=2.807 σ=1.458	Log-Normal	μ=14.035 σ=7.290	Log-Normal	μ=16.841 σ=8.748
	Corrosion	Log-Normal	μ=1.520 σ=0.790	Log-Normal	μ=7.601 σ=3.948	Log-Normal	μ=9.121 σ=3.948
	NASF	Log-Normal	μ=4.055 σ=2.106	Log-Normal	μ=11.585 σ=6.017	Log-Normal	μ=15.639 σ=8.123

Table 7.16: Table related to the distributions of the Main Analysis with respect to Environmental Impact

8. Conclusions

Statistical Analysis of the existent data that were extracted by the concerned database, gave us the capability to comprehend the behavior of RoPax vessels which suffered from Non Accidental Structural Failures (NASF). Also, the frequency of NASF with regards to the other accidents had become known. So, aggregated results that were derived by the occurrence of the Statistical Analysis are presented below:

- During the period of 1985-2016, IHS Database had recorded 3,707 incidents that had been related to RoPax ships.
- Database incidents had indicated that the most frequent kind of failure was the category of Hull/Machinery Damage (29.32%).
- Contact, Wrecked/Stranded and Collision categories had been the other most significant ones in RoPax ships with their percentage respectively 15.94%, 13.14%, 12.25%.
- The 45.43% of the casualties had occurred in RoPax vessels with 0-1,000GT (1684 incidents).
- The other 25.17% of the incidents had been characterized by ships with Gross Tonnage values between 1,000-4,000GT (933accidents).
- The remaining 29.40% of the incidents was concerned ships that had a value, higher than 4,000GT.
- Whole Fleet's age which was involved in the accidents was quite contemporary as a 33.77% concerned ships with year of built after 2006 (0-10 years old).
- Another 19.01% had been represented ships that had been built the period of 1996-2006 (10-20 years old).
- NASF had been recognized in 200 occasions, which was about the 5.4% of the existent accidents.
- Most of them, a 65%, had been observed during a day while the weather had been usually heavy (76%).
- Loss of Water Integrity (LOWI) had been found in 76 cases for Ships that had suffered from NASF.
- A perceivable percentage of 16.5% of the incidents had led to the loss of ship while an estimated 2% showed that ships had been refloated.
- Scrap of the ship was observed for the 1.5% of the NASF incidents, while the significant casualties reached the 41.5% of the percentage.
- RoPax ships, which had appeared with corrosion, constituted a 35.5% of the NASF casualties.
- A large number of ships which had taken into consideration and had been participated to the research of the NASF incidents were ships with 4,000GT and below, as their percentage was 58%.

Furthermore, having accomplished Risk Analysis on RoPax vessels, the characteristics of each ship's failure that had been subjected to NASF and their potential consequences had become known. The most crucial of them are:

- Event tree analysis for corrosion failures indicated that ships with 4,000GT and below had a higher possibility of leading to ship's Total Loss (20.5%) than the corresponding one of ships with Gross Tonnage bigger than 4,000GT (6.3%). That is quite reasonable as ships with higher GT usually carry more passengers and the maintenance is more regular.
- Even though Total Loss in corrosion failures occurrence was more frequent in the Small Class of RoPax, Potential Environmental Impact (PEI) had a greater value for the Large class, 4.22 instead of 3.43 according to the Event Tree Analysis. That happened due to the fact that bigger vessels had the necessity of bigger tank capacities so specific class ran higher risk of spilling large amount of oil, even though it had been released in few cases. This tendency was justified by Monte Carlo simulation too where the cumulative risk for the Large class was 9.12 in contrast to that of Small Class which was 5.44.
- As far as Potential Damage to Property (PDP) is concerned throughout the corrosion failures, it must be mentioned that Event Tree Analysis had given the result that small class of RoPax vessels had as risk contributor the value of 4.139 while in large class was 3.522. Something which seemed to be inaccurate due to the fact that vessels with larger amount of Gross Tonnage usually cost more and the loss of property is more serious. But because of the values of GT which suffered by those failures and the probabilities of Total Loss, Refloat and Scrap, this result was come up. On the contrary, Monte Carlo simulation due to the fact contained GT values of all fleet led us to the conclusion that the theoretical value of the cumulative risk for corrosion failures was 7.86 for large vessels and 4.71 for the smaller ones.
- Fatigue failures had been assessed to cause the loss of the ship (either by Total Loss or by Scrap) with a percentage of 27.27% for Ships<4,000GT and the percentage of 15.39%, which contained Total Loss, Refloat and Scrap probabilities, had been estimated for Ropax ships>4,000GT.
- Environmental consequences had caused by fatigue failures in both categories of the ships, Small and Large class. Event tree Analysis gave the outcomes that Large class's cumulative risk is 4.58, whereas Small class's relative risk is 7.32. On the other hand, Monte Carlo simulation gave the theoretical value of 5.44 for the small category of RoPax which were observed by fatigue failures, and 16.84 for the Large class. It must remarked that discrepancies are owed to the difference of the tank capacities of the ships which recorded with an accident and ships' tank capacities which can theoretically be involved in a casualty.
- The results of the research for fatigue failures with respect to Property to Damage consequences assisted us to draw a safe conclusion, as Monte Carlo simulation and Event Tree Analysis gave us similar effects with regards to

which class was in a more critical danger. Having interpreted Monte Carlo simulation figures, cumulative risk for RoPax Ships<4,000GT found to be 5.422, while PDP for the other category related to size was 13.807. Similarly, results of relative Event Tree were 4.909 for the Small Class and 10.094 for the Large class of RoPax vessels.

- It was observed during the process of this research that for corrosion failures, fatalities and injuries had not occurred.
- Contrariwise, incidents which derived by fatigue failures were noticed to have caused injuries and fatalities. The risk contributor with respect to the loss of life for the Small class with fatigue failures was estimated about 0.150 while Potential Loss of Life (PLL) for the Large Class with fatigue failures was assessed 0.0013 by the respective Event Tree. If these outcomes compared with each other, it is absolutely comprehensible that incidents of ships with lower Gross Tonnage are more vulnerable to be accompanied by loss of life. But it must remarked that even though accidents in RoPax ships with large GT is less frequent, a great attention to their safety must be given as they transfer more passengers and as a result an undesired incident could cause a large number of fatalities.
- When casualties were distinguished in two categories in relation to their size without having taken into consideration the type of NASF (corrosion or fatigue), some imperative outcomes with respect to their consequences had emerged. Initially, pollution's cumulative risk for the Small class of specific vessels calculated with Event Tree Method 3.84, while Monte Carlo Simulation led us to the result that expected value of concerned category was 4.09. These two values found to be very close, so it can be derived that the sample was satisfying and Event Tree method could have been compatible for the whole fleet too. Large class's risk contributors of the pollution were 5.16 by the Event Tree and 15.64 by the simulation. It is reasonable to have this difference because whole fleet was consisted of bigger ships than those which recorded with NASF. Furthermore, PDP for the Small class found 4.660 with the assistance of Event Tree method while relative simulation gave the value of 5.030. According to the logic, PDP for the Large class gave higher values that were derived by Event Tree and Monte Carlo methods and were 7.23 and 11.03 respectively.

9. Proposals for Future Work

This thesis focused on the statistical and the risk analysis of Non Accidental Structural Failures (NASF) that occurred or could occur on RoPax ships. A category of incidents which has concerned maritime community very few times and in even few occasions, researches with respect to their impacts on RoPax ships have developed.

It is vital to be mentioned that the existence of a database which would contain more information with respect to ship characteristics and a higher number of incidents, which would have identified by itself this category of incidents (NASF), could have given more accurate and striking outcomes. Also, if the pollution rates were known, then assumptions for oil spills can be deterred and lead us to more precise results. Another issue that could be elaborated in a future thesis is the assessment of the total risk for each ship size category with regards to the loss of life. Furthermore, current research could be further analysed by developing models to determine the theoritical probabilities for the occurrence of each Degree of Severity so as to estimate with a more verified method for the values of the consequences for the whole fleet without taking into consideration the recorded incidents. Finally, similar studies on NASF which could assess the consequences of this kind of incidents should perform for other types of ships too.

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IMO MSC 83/INF.8 Formal Safety Assessment FSA –Container Vessels

IMO MSC 85/INF.2 Formal Safety Assessment FSA –Cruise Ships

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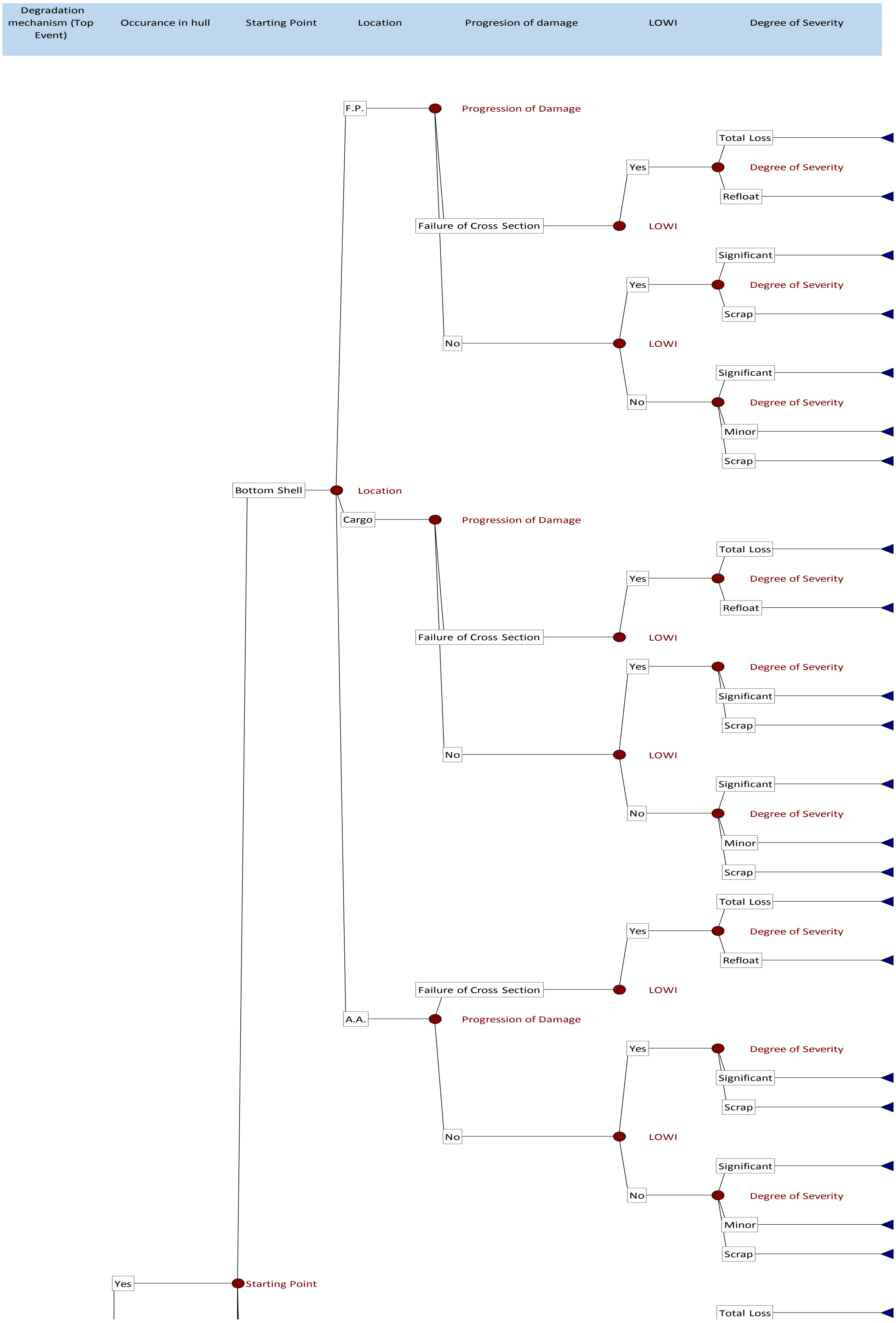
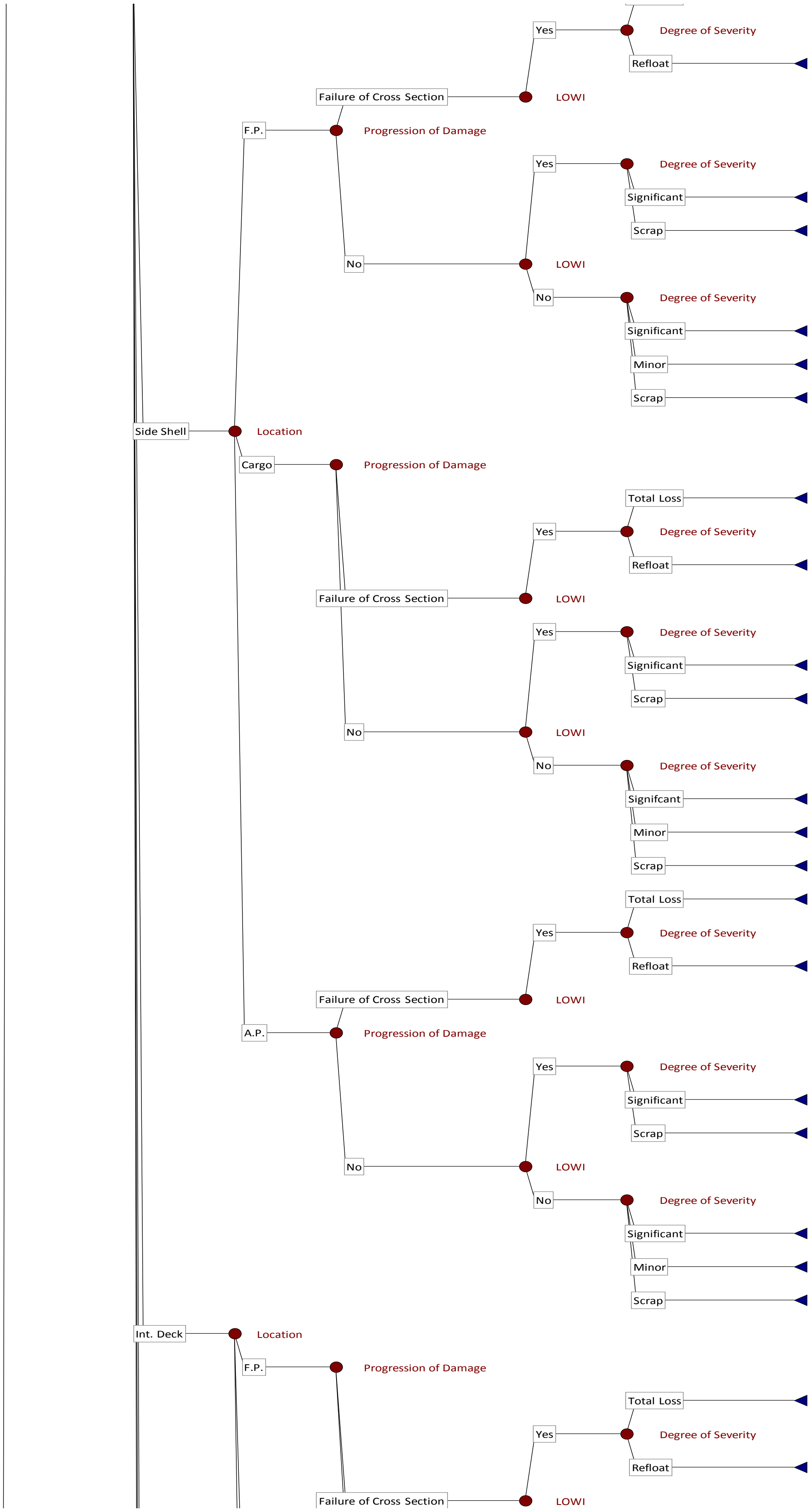
APPENDIX A

FIGURE A.1

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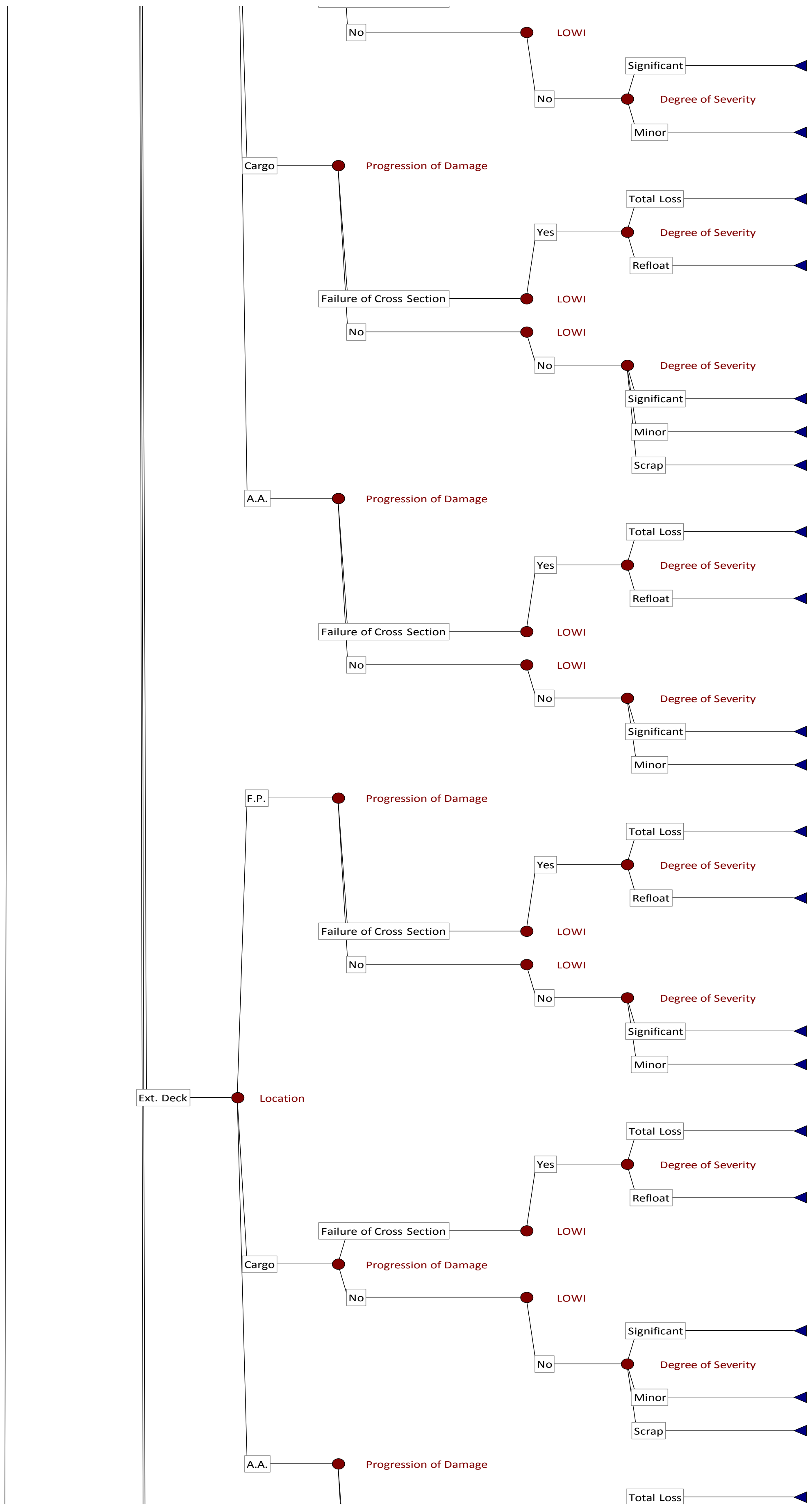
Degree of Severity
Refloat
Failure of Cross Section
LOWI
F.P.
Progression of Damage
Yes
Degree of Severity
Significant
Scrap
No
LOWI
No
Degree of Severity
Significant
Minor
Scrap
Side Shell
Location
Cargo
Progression of Damage
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
Yes
Degree of Severity
Significant
Scrap
No
LOWI
No
Degree of Severity
Signifcant
Minor
Scrap
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
A.P.
Progression of Damage
Yes
Degree of Severity
Significant
Scrap
No
LOWI
No
Degree of Severity
Significant
Minor
Scrap
Int. Deck
Location
F.P.
Progression of Damage
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI



No
LOWI
Significant
No
Degree of Severity
Minor
Cargo
Progression of Damage
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
No
LOWI
No
Degree of Severity
Significant
Minor
Scrap
A.A.
Progression of Damage
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
No
LOWI
No
Degree of Severity
Significant
Minor
F.P.
Progression of Damage
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
No
LOWI
No
Degree of Severity
Significant
Minor
Ext. Deck
Location
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
Cargo
Progression of Damage
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Significant
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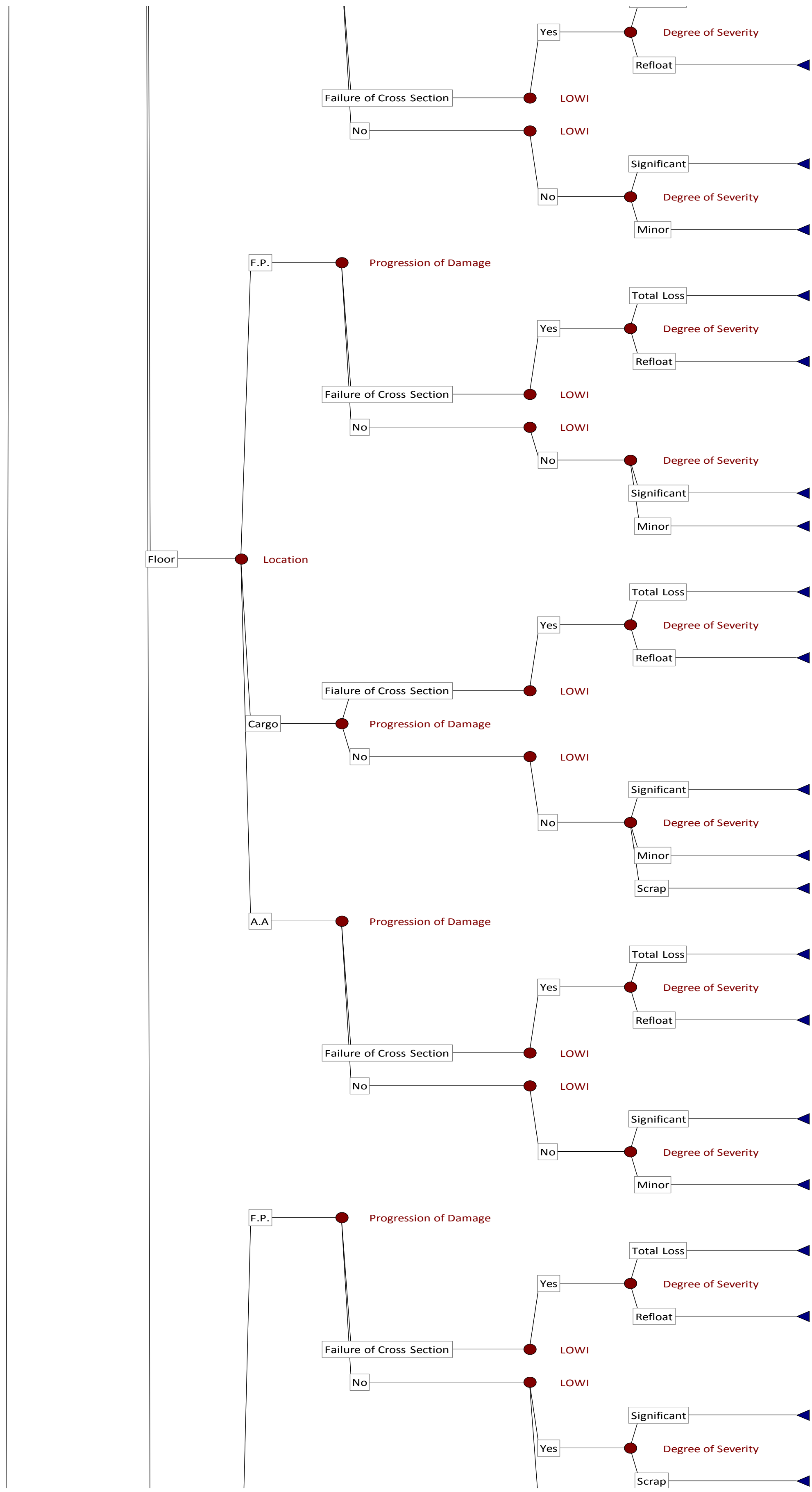
Degree of Severity
Minor
Scrap
A.A.
Progression of Damage
Total Loss



Degree of Severity
Yes
Refloat
Failure of Cross Section
LOWI
No
LOWI
Significant
No
Degree of Severity
Minor
F.P.
Progression of Damage
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
No
LOWI
No
Degree of Severity
Significant
Minor
Floor
Location
Total Loss
Yes
Degree of Severity
Refloat
Fialure of Cross Section
LOWI
Cargo
Progression of Damage
No
LOWI
Significant
No
Degree of Severity
Minor
Scrap
A.A
Progression of Damage
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
No
LOWI
Significant
No
Degree of Severity
Minor
F.P.
Progression of Damage
Total Loss
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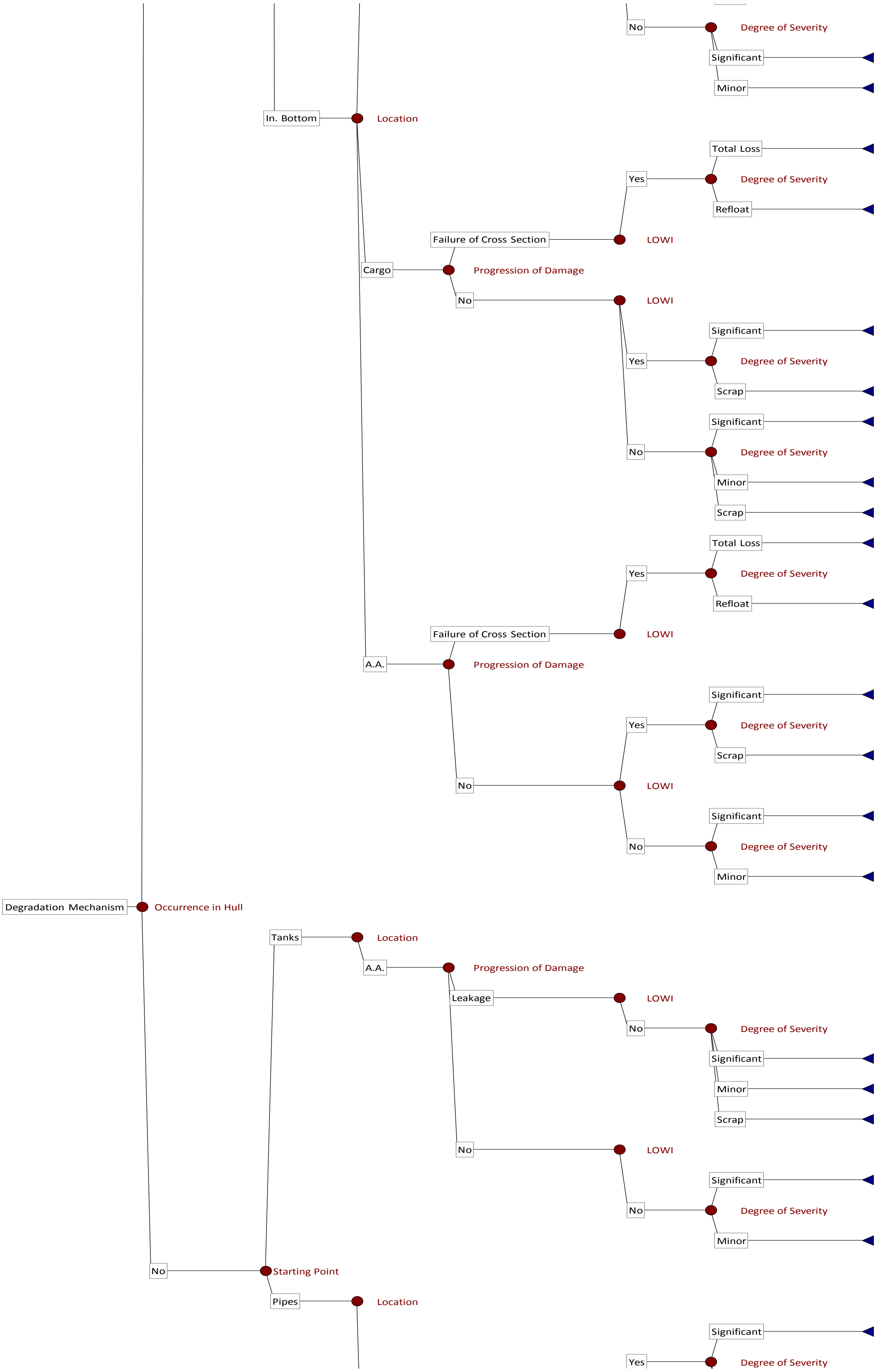
Degree of Severity
Refloat
Failure of Cross Section
LOWI
No
LOWI
Significant
Yes
Degree of Severity
Scrap


No
Degree of Severity
Significant
Minor
In. Bottom
Location
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
Cargo
Progression of Damage
No
LOWI
Significant
Yes
Degree of Severity
Scrap
Significant
No
Degree of Severity
Minor
Scrap
Total Loss
Yes
Degree of Severity
Refloat
Failure of Cross Section
LOWI
A.A.
Progression of Damage
Significant
Yes
Degree of Severity
Scrap
No
LOWI
Significant
No
Degree of Severity
Minor
Degradation Mechanism
Occurrence in Hull
Tanks
Location
A.A.
Progression of Damage
Leakage
LOWI
No
Degree of Severity
Significant
Minor
Scrap
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LOWI
Significant
No
Degree of Severity
Minor
No
Starting Point
Pipes
Location
Significant
Yes
Degree of Severity

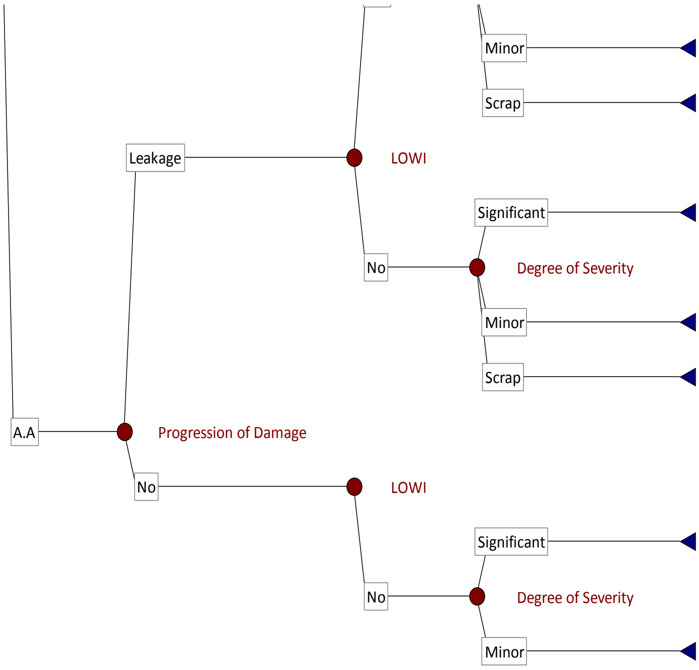
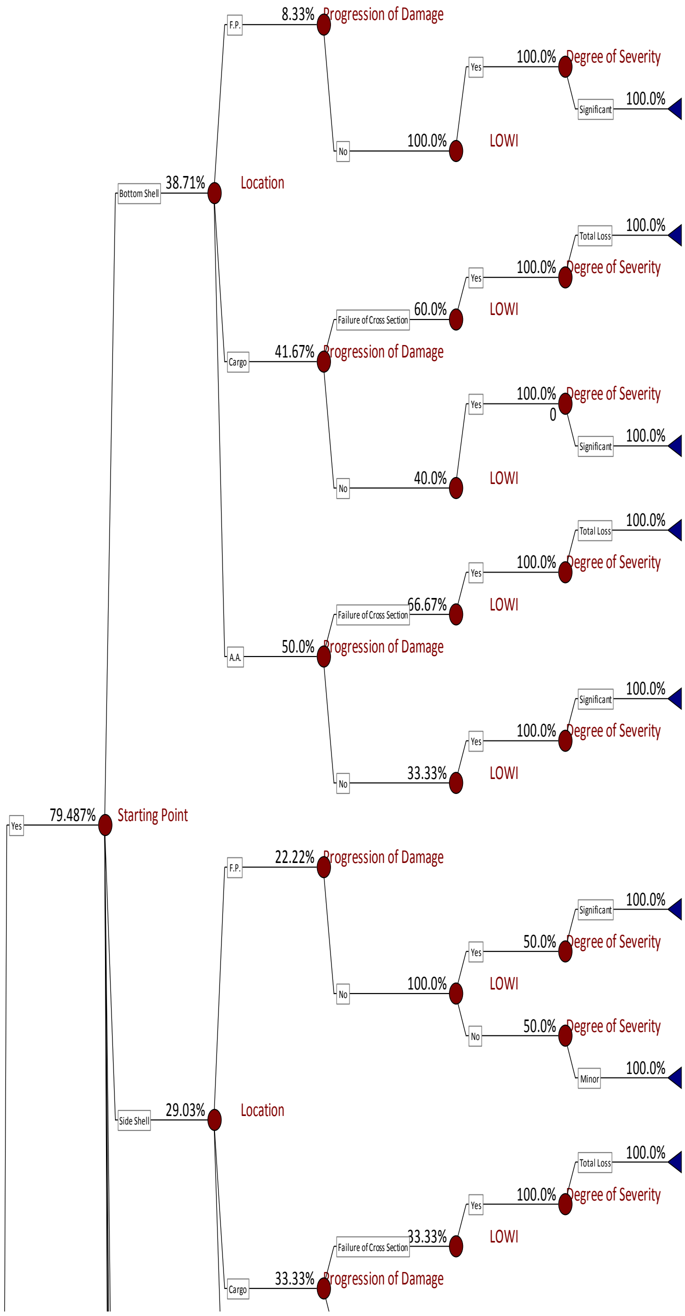


Figure A.1: Theoretical Event Tree for RoPax vessels with NASF

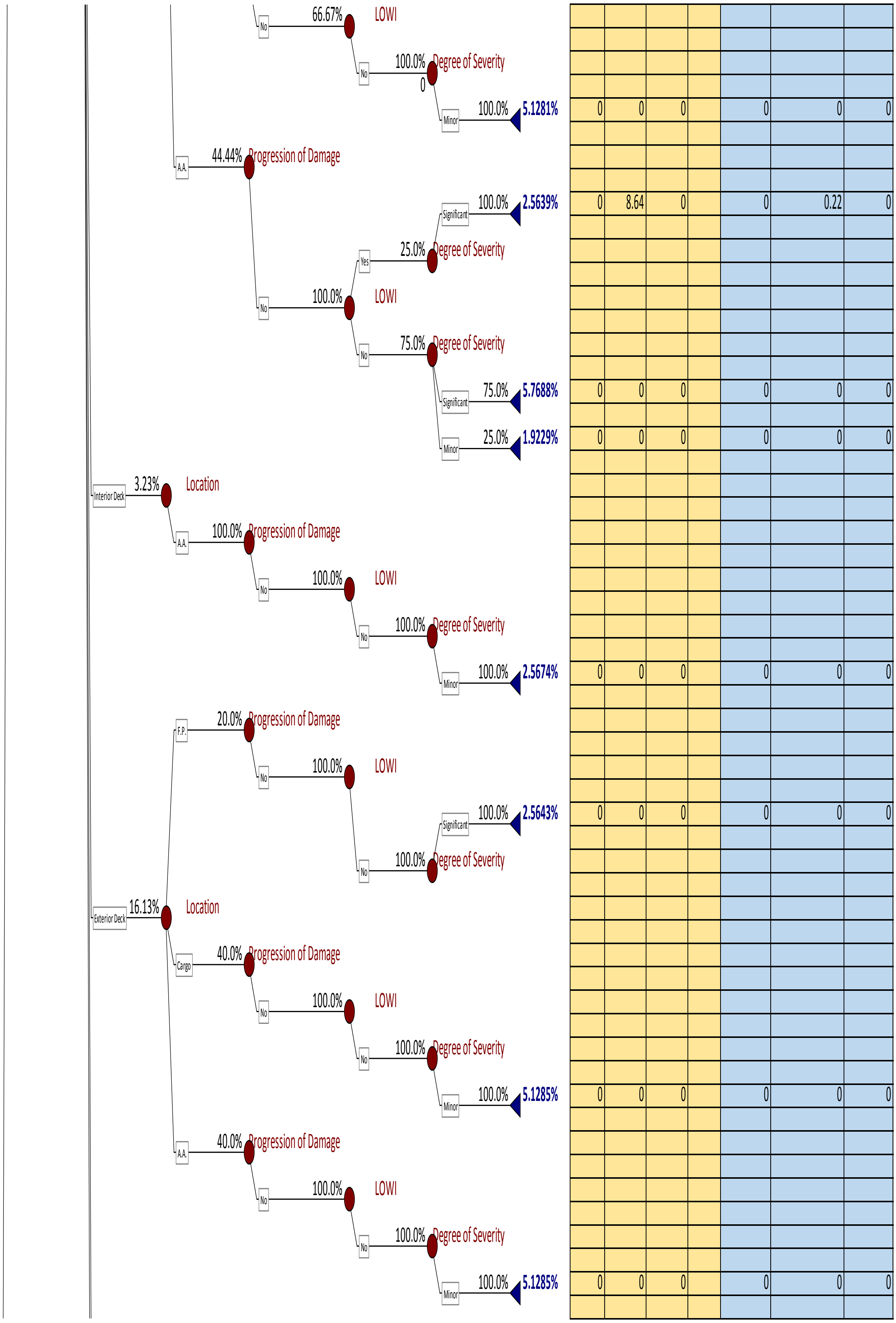
APPENDIX B

FIGURE B.1

Degradation Mechanicsm (Small GT)	Occurrence in Hull	Starting Point	Location	Progresion of damage	LOWI	Degree of Severity	Probabilty of Scenario	Consequences				Cumulative Risk Contribution		
								Loss of Life	Pollution (tonnes)	Damage to property (million)		Potential Loss of Life (PLL) per ship's life cycle passengers	Potential Environmental Impact (PEI) (tonnes per ship's life cycle)	Potential Damage to Property (PDP) (million € per ship's life cycle)
												0	3.43	4.139



Probabilty of Scenario	Loss of Life	Pollution (tonnes)	Damage to property (million)		PLL	PEI	PDP
2.5631%	0	3	0		0	0.08	0
7.693%	0	0	14.18		0	0	1.091
5.1286%	0	0	0		0	0	0
10.257%	0	30.5	17.82		0	3.13	1.828
5.1277%	0	0	0		0	0	0
2.5639%	0	0	0		0	0	0
2.5639%	0	0	0		0	0	0
2.5636%	0	0	33.69		0	0	0.864


66.67%
LOWI
100.0%
Degree of Severity
Minor
100.0%
5.1281%
44.44%
Progression of Damage
A.A.
Significant
100.0%
2.5639%
8.64
0.22
25.0%
Degree of Severity
Yes
100.0%
LOWI
75.0%
Degree of Severity
75.0%
5.7688%
25.0%
1.9229%
Interior Deck
3.23%
Location
100.0%
Progression of Damage
100.0%
LOWI
100.0%
Degree of Severity
100.0%
2.5674%
F.P.
20.0%
Progression of Damage
100.0%
LOWI
100.0%
2.5643%
100.0%
Degree of Severity
Exterior Deck
16.13%
Location
Cargo
40.0%
Progression of Damage
100.0%
LOWI
100.0%
Degree of Severity
100.0%
5.1285%
40.0%
Progression of Damage
100.0%
LOWI
100.0%
Degree of Severity
100.0%
5.1285%

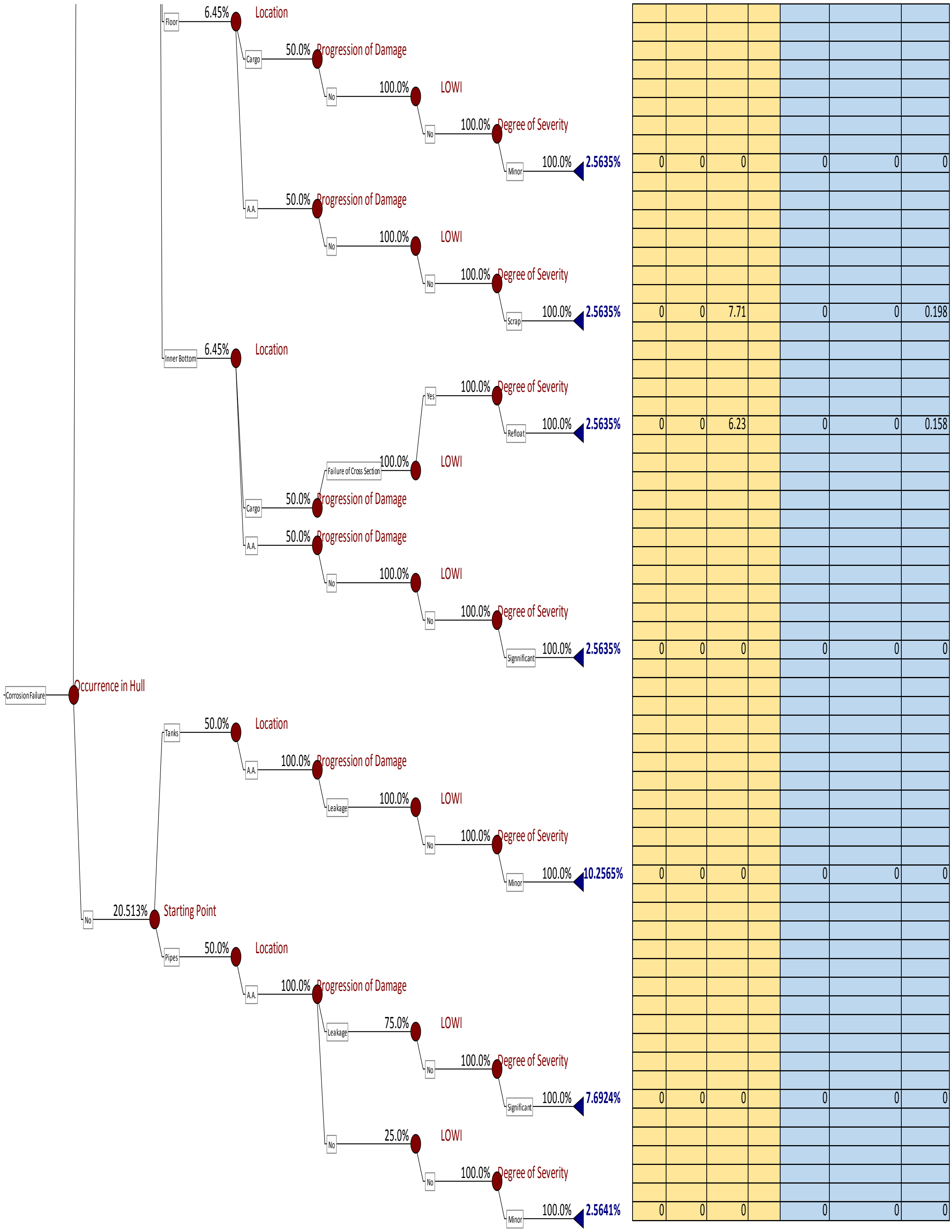
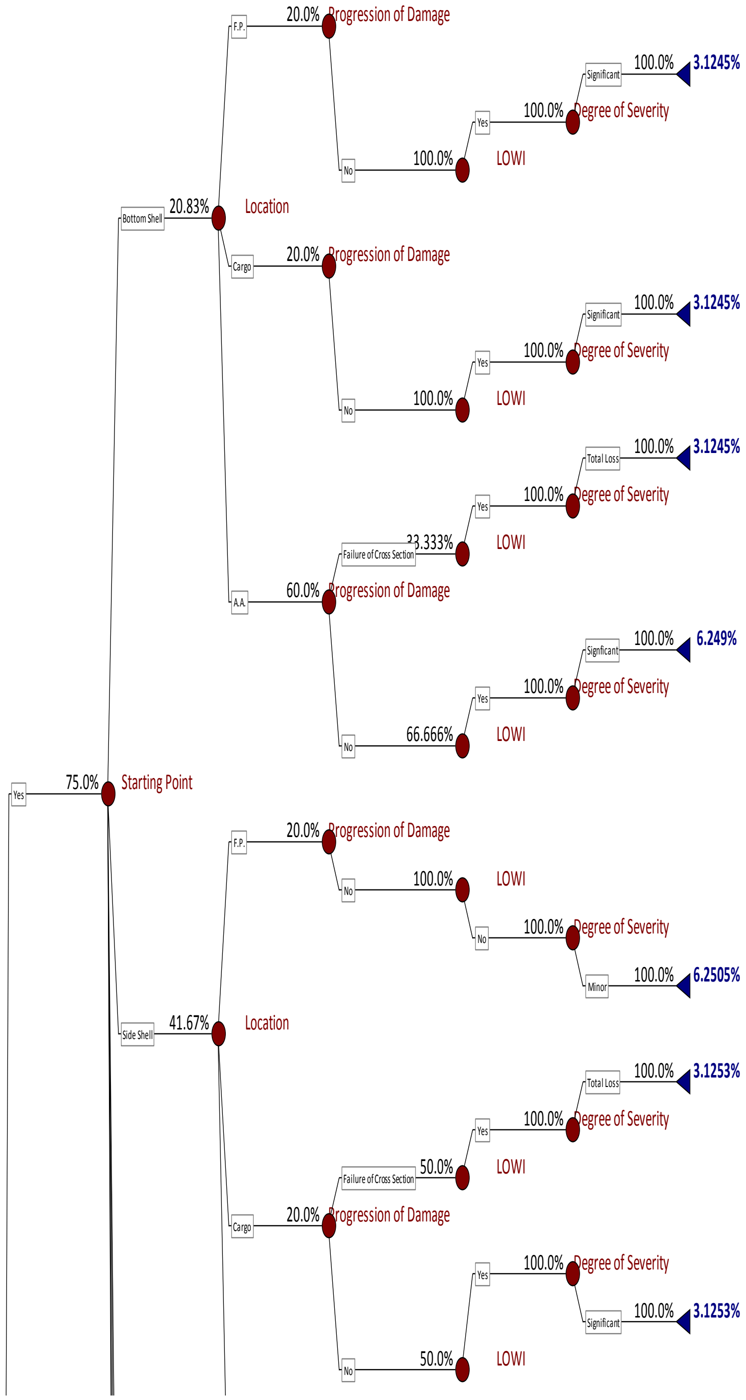
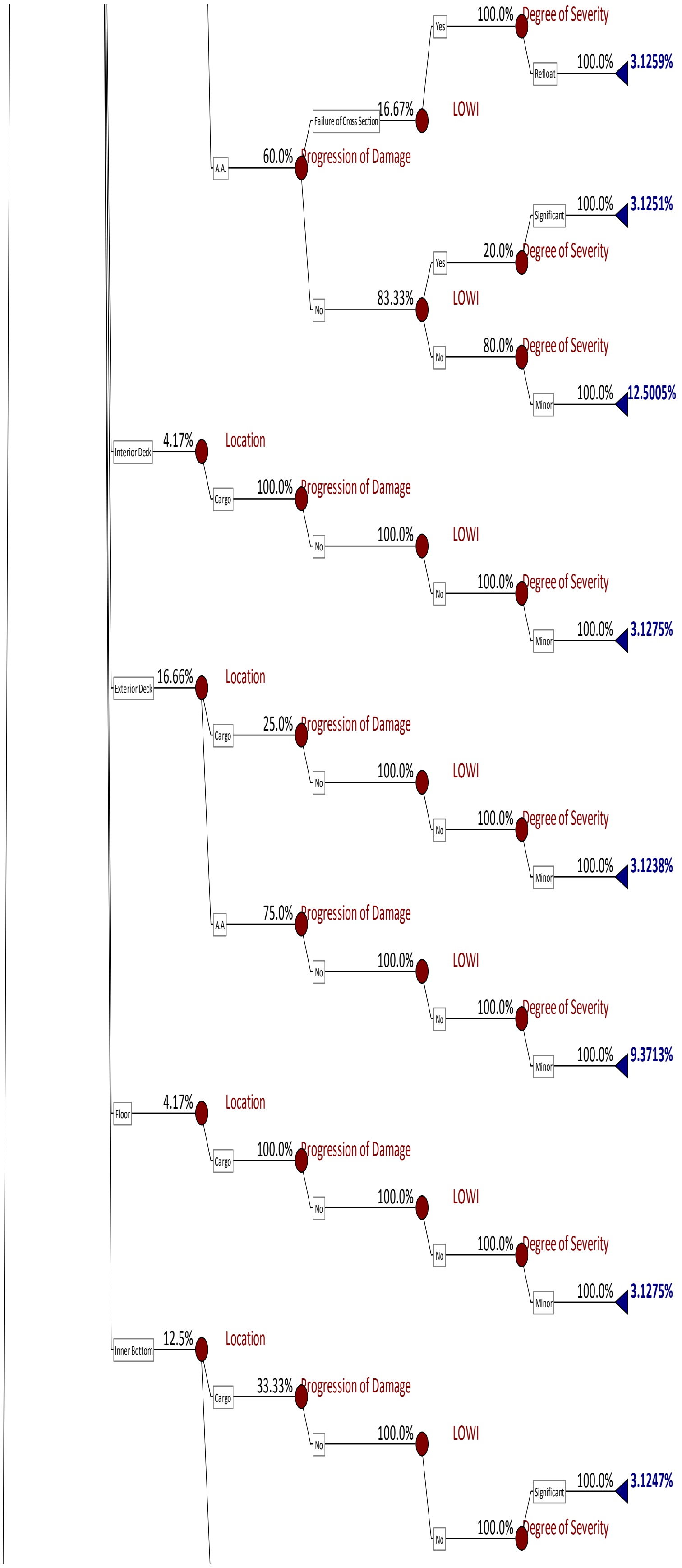


Figure B.1: Event Tree for RoPax vessels with 0-4,000GT under Corrosion failures

FIGURE B.2

Degradation Mechanism (Large GT)	Occurrence in Hull	Starting Point	Location	Progression of damage	LOWI	Degree of Severity	Probabilty of Scenario	Consequences: Loss of Life	Consequences: Pollution (tonnes)	Consequences: Damage to property (million)		Cumulative Risk Contribution: Potential Loss of Life (PLL) per ship's life cycle passengers	Cumulative Risk Contribution: Potential Environmental Impact (PEI) (tonnes per ship's life cycle)	Cumulative Risk Contribution: Potential Damage to Property (PDP) (million € per ship's life cycle)
												0	4.22	3.522
							3.1245%	0	3	0		0	0.09	0
							3.1245%	0	1.1	0		0	0.03	0
							3.1245%	0	128.8	48.31		0	4.02	1.51
							6.249%	0	0	0		0	0	0
							6.2505%	0	0	0		0	0	0
							3.1253%	0	0	52.47		0	0	1.64
							3.1253%	0	2.5	0		0	0.08	0





0	0	11.9		0	0	0.372
0	0	0		0	0	0
0	0	0		0	0	0
0	0	0		0	0	0
0	0	0		0	0	0
0	0	0		0	0	0
0	0	0		0	0	0
0	0	0		0	0	0

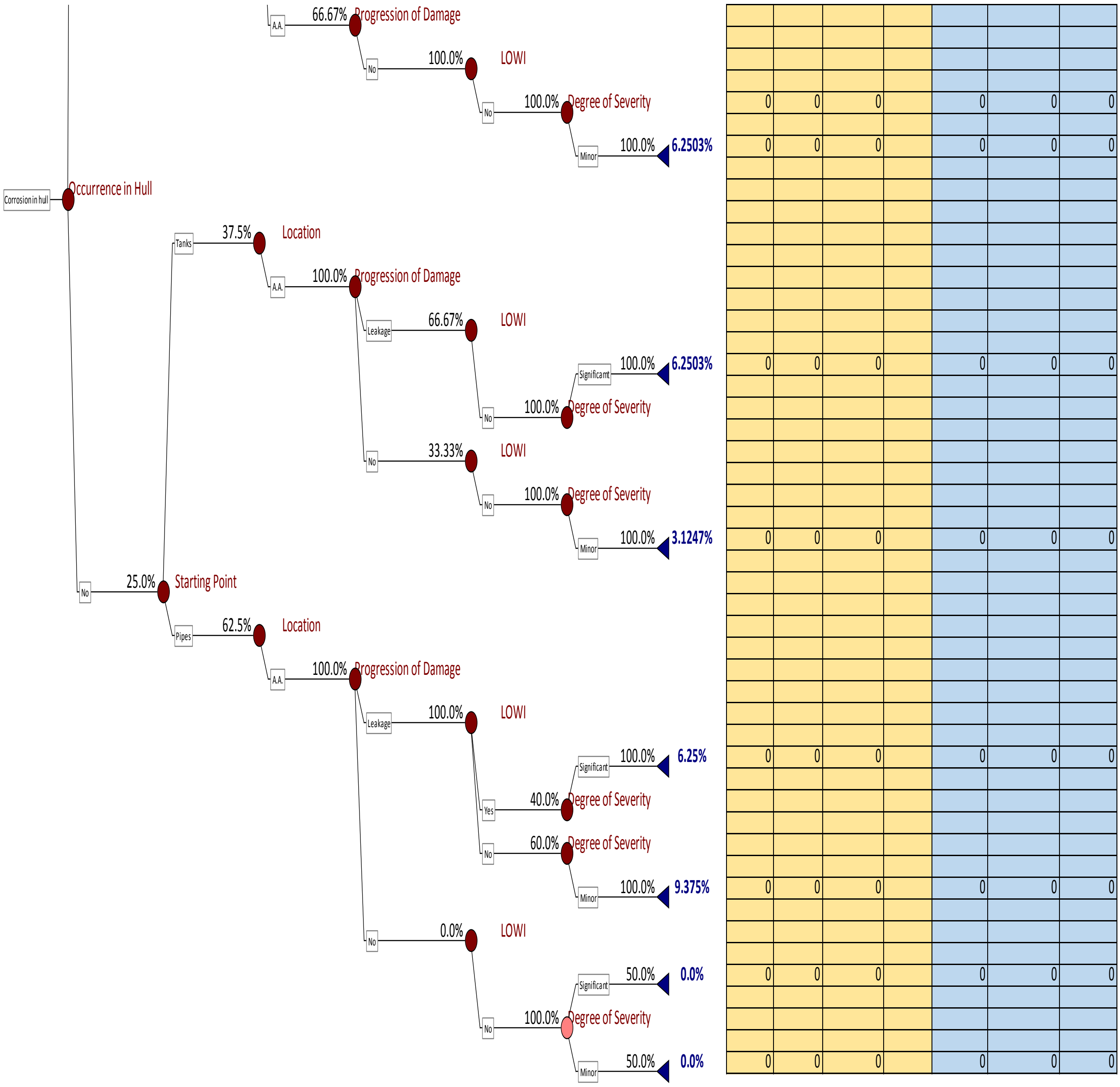
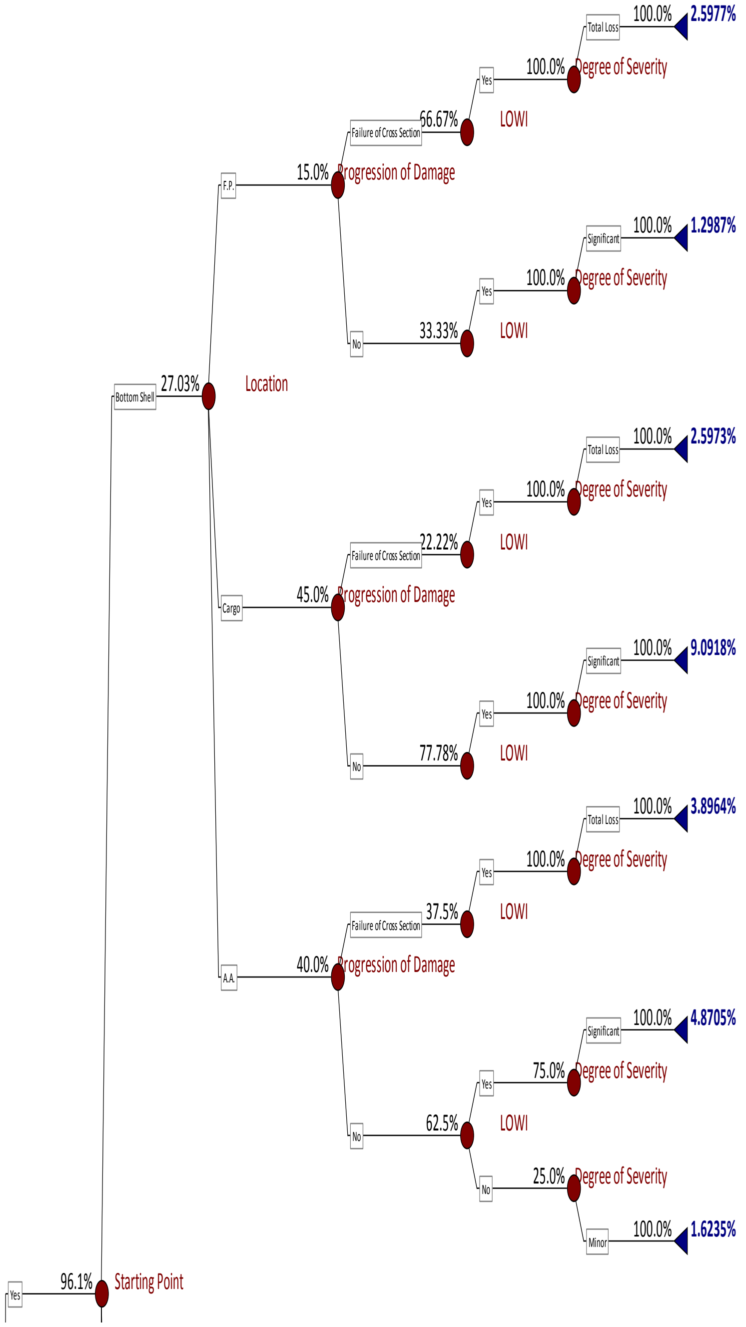
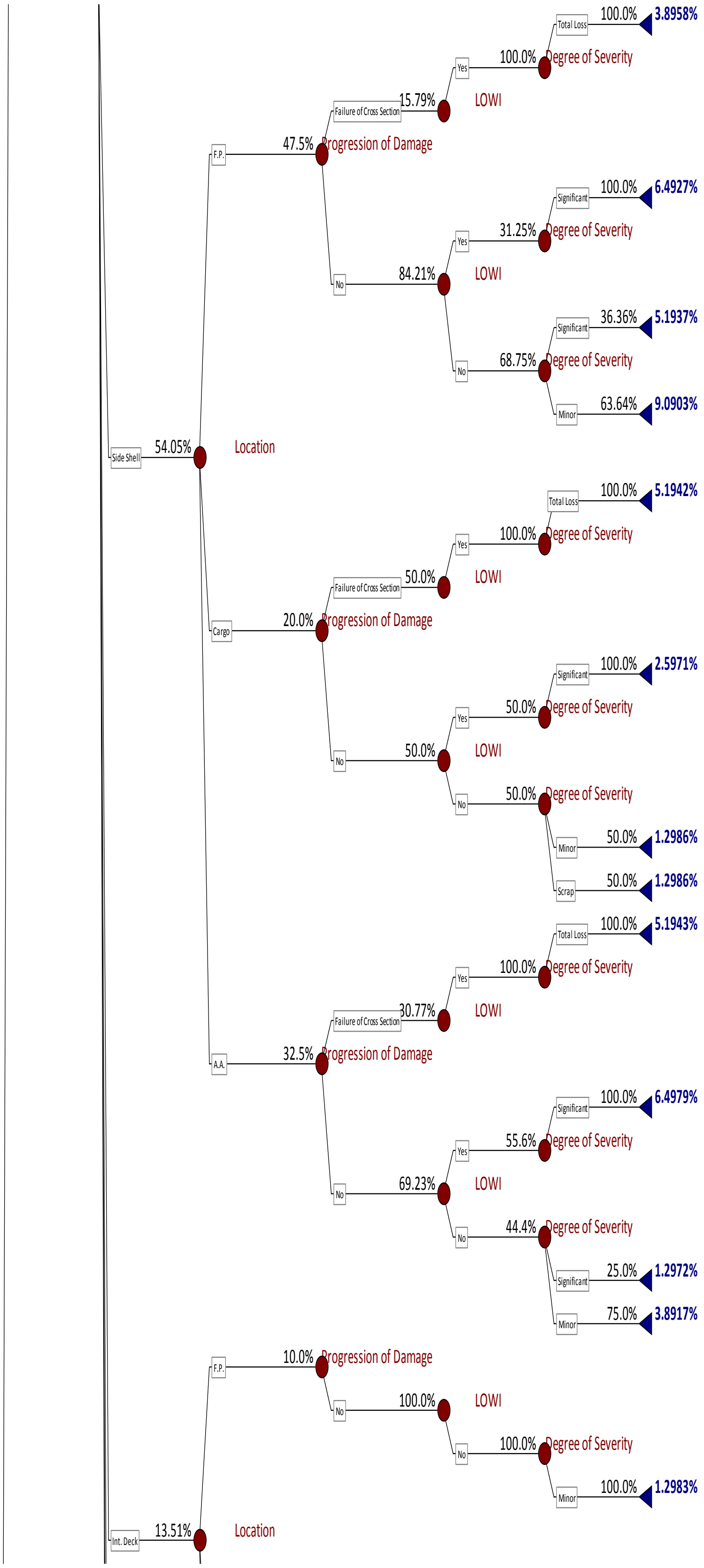


Figure B.2: Event Tree for RoPax vessels with 4,000GT and above under Corrosion failures

FIGURE B.3

Degradation Mechanism (Small GT)	Occurrence in Hull	Starting Point	Location	Progresion of damage	LOWI	Degree of Severity	Probabilty of Scenario	Consequences: Loss of Life	Consequences: Pollution (tonnes)	Consequences: Damage to property (million)		Cumulative Risk Contribution: Potential Loss of Life (PLL)	Cumulative Risk Contribution: Potential Environmental Impact (PEI)	Cumulative Risk Contribution: Potential Damage to Property (PDP)
												0.151	4.78	4.909
							2.5977%	0	0	38.35		0	0	0.996
							1.2987%	0	0	0		0	0	0
							2.5973%	1.5	0	40.56		0.039	0	1.053
							9.0918%	0	0	0		0	0	0
							3.8964%	1	59.97	5.95		0.035	2.34	0.232
							4.8705%	0	0	0		0	0	0
							1.6235%	0	0	0		0	0	0





1.66	44.17	14.2		0.065	1.72	0.553
0	0	0		0	0	0
0	0	0		0	0	0
0	0	0		0	0	0
0	0	15		0	0	0.779
0	0	0		0	0	0
0	0	0		0	0	0
0	0	7.49		0	0	0.097
0	13.8	17.44		0	0.72	0.906
0.16	0	0		0.010	0	0
0	0	0		0	0	0
0	0	0		0	0	0
0	0	0		0	0	0

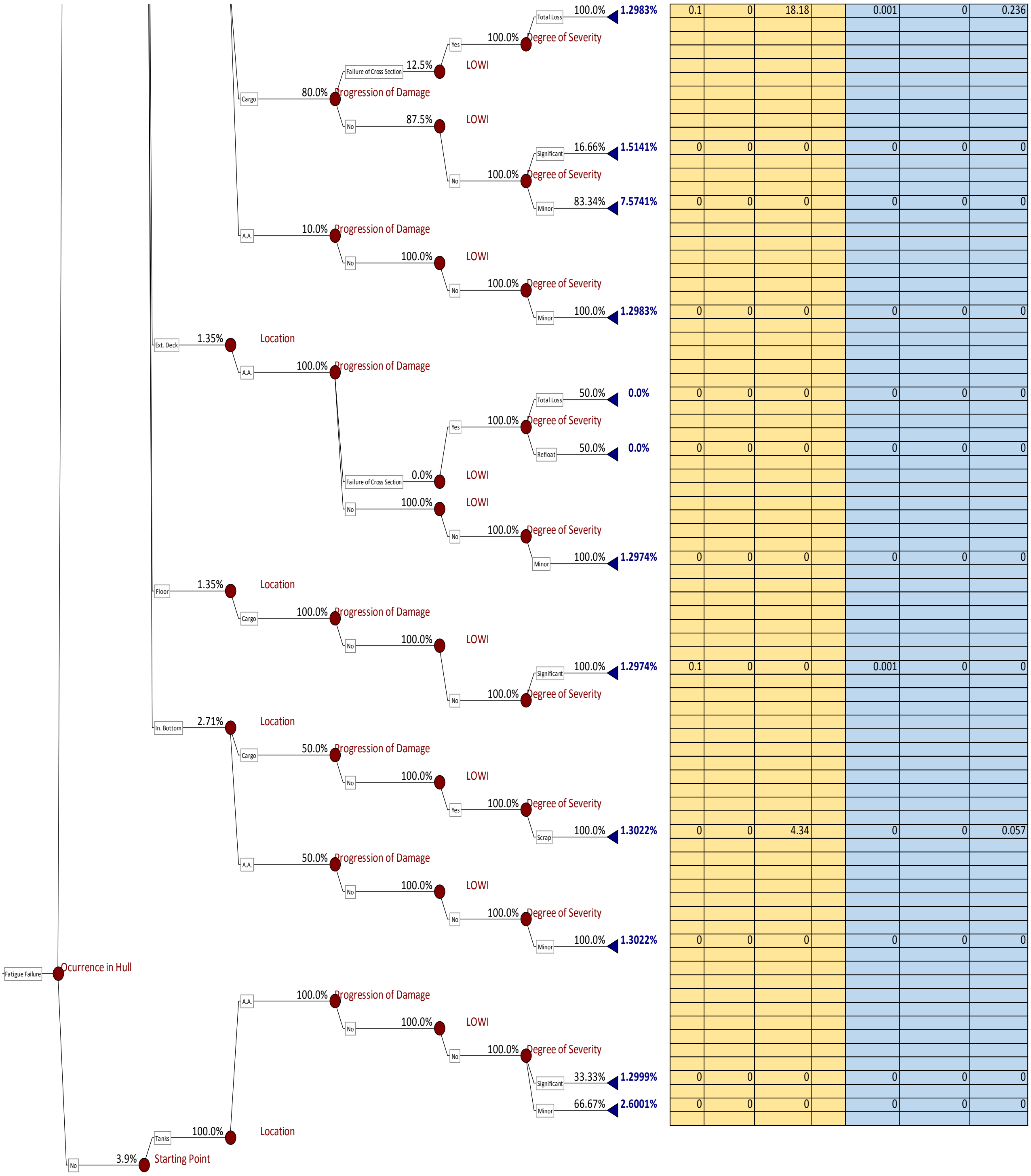
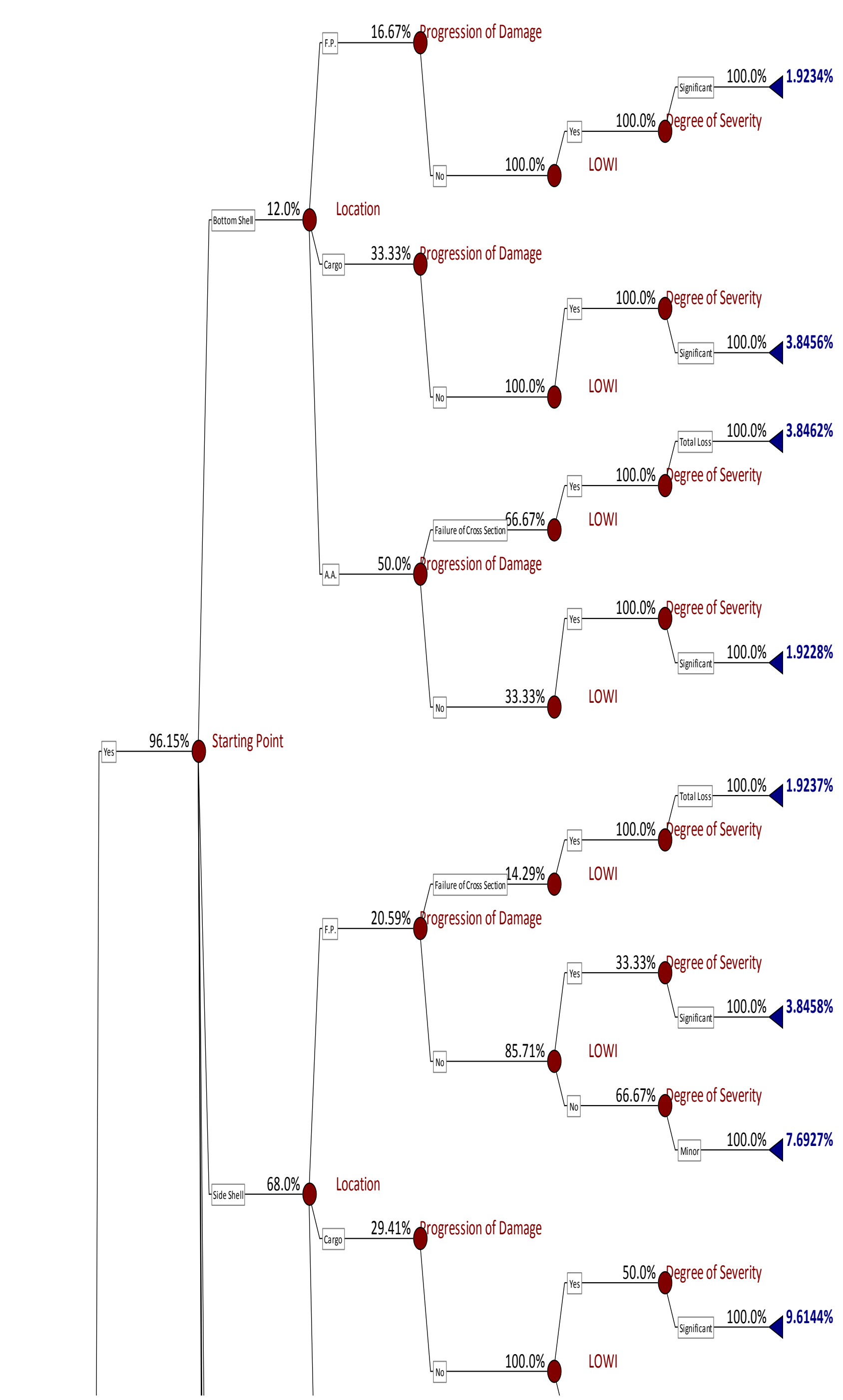
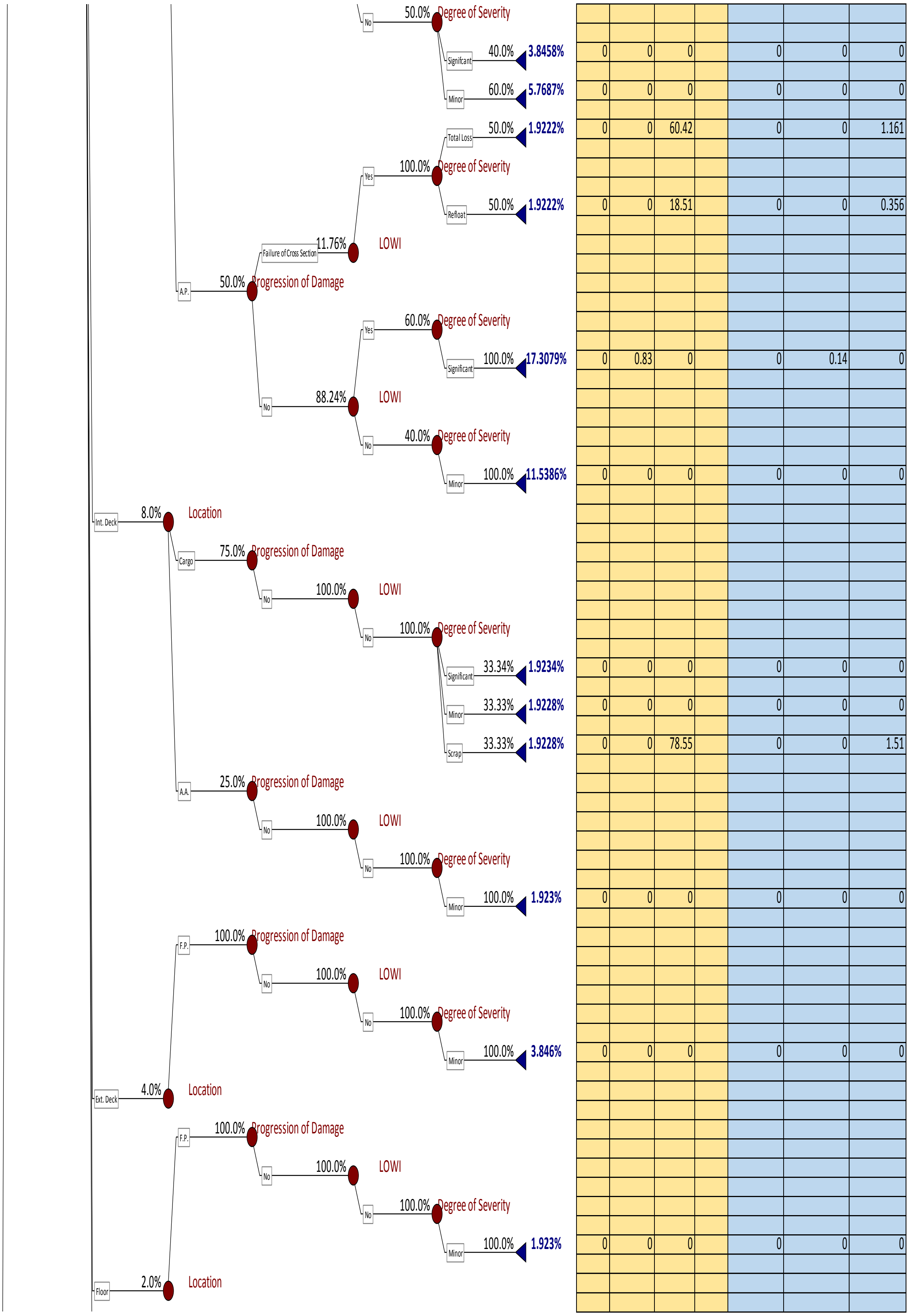


Figure B.3: Event Tree for RoPax vessels with 0- 4,000GT under Fatigue failures

FIGURE B.4

Degradation Mechanism (Large GT)	Occurrence in Hull	Starting Point	Location	Progresion of damage	LOWI	Degree of Severity	Probabilty of Scenario	Consequences: Loss of Life	Consequences: Pollution (tonnes)	Consequences: Damage to property (million)		Cumulative Risk Contribution: Potential Loss of Life (PLL) per ship's life cycle passengers	Cumulative Risk Contribution: Potential Environmental Impact (PEI) (tonnes per ship's life cycle)	Cumulative Risk Contribution: Potential Damage to Property (PDP) (million € per ship's life cycle)
												0.0013	4.58	10.094
							1.9234%	0	0	0		0	0	0
							3.8456%	0	0	0		0	0	0
							3.8462%	0	72	113.77		0	2.77	4.376
							1.9228%	0	0	0		0	0	0
							1.9237%	0	87	52.67		0	1.67	1.013
							3.8458%	0.035	0	0		0.0013	0	0
							7.6927%	0	0	0		0	0	0
							9.6144%	0	0	0		0	0	0





No
50.0% Degree of Severity
Significant 40.0% 3.8458% 0 0 0 0 0 0
Minor 60.0% 5.7687% 0 0 0 0 0 0
Total Loss 50.0% 1.9222% 0 0 60.42 0 0 1.161
Yes 100.0% Degree of Severity
Refloat 50.0% 1.9222% 0 0 18.51 0 0 0.356
Failure of Cross Section 11.76% LOWI
A.P. 50.0% Progression of Damage
Yes 60.0% Degree of Severity
Significant 100.0% 17.3079% 0 0.83 0 0 0.14 0
No 88.24% LOWI
No 40.0% Degree of Severity
Minor 100.0% 11.5386% 0 0 0 0 0 0
Int. Deck 8.0% Location
Cargo 75.0% Progression of Damage
No 100.0% LOWI
No 100.0% Degree of Severity
Significant 33.34% 1.9234% 0 0 0 0 0 0
Minor 33.33% 1.9228% 0 0 0 0 0 0
Scrap 33.33% 1.9228% 0 0 78.55 0 0 1.51
A.A. 25.0% Progression of Damage
No 100.0% LOWI
No 100.0% Degree of Severity
Minor 100.0% 1.923% 0 0 0 0 0 0
F.P. 100.0% Progression of Damage
No 100.0% LOWI
No 100.0% Degree of Severity
Minor 100.0% 3.846% 0 0 0 0 0 0
Ext. Deck 4.0% Location
F.P. 100.0% Progression of Damage
No 100.0% LOWI
No 100.0% Degree of Severity
Minor 100.0% 1.923% 0 0 0 0 0 0
Floor 2.0% Location

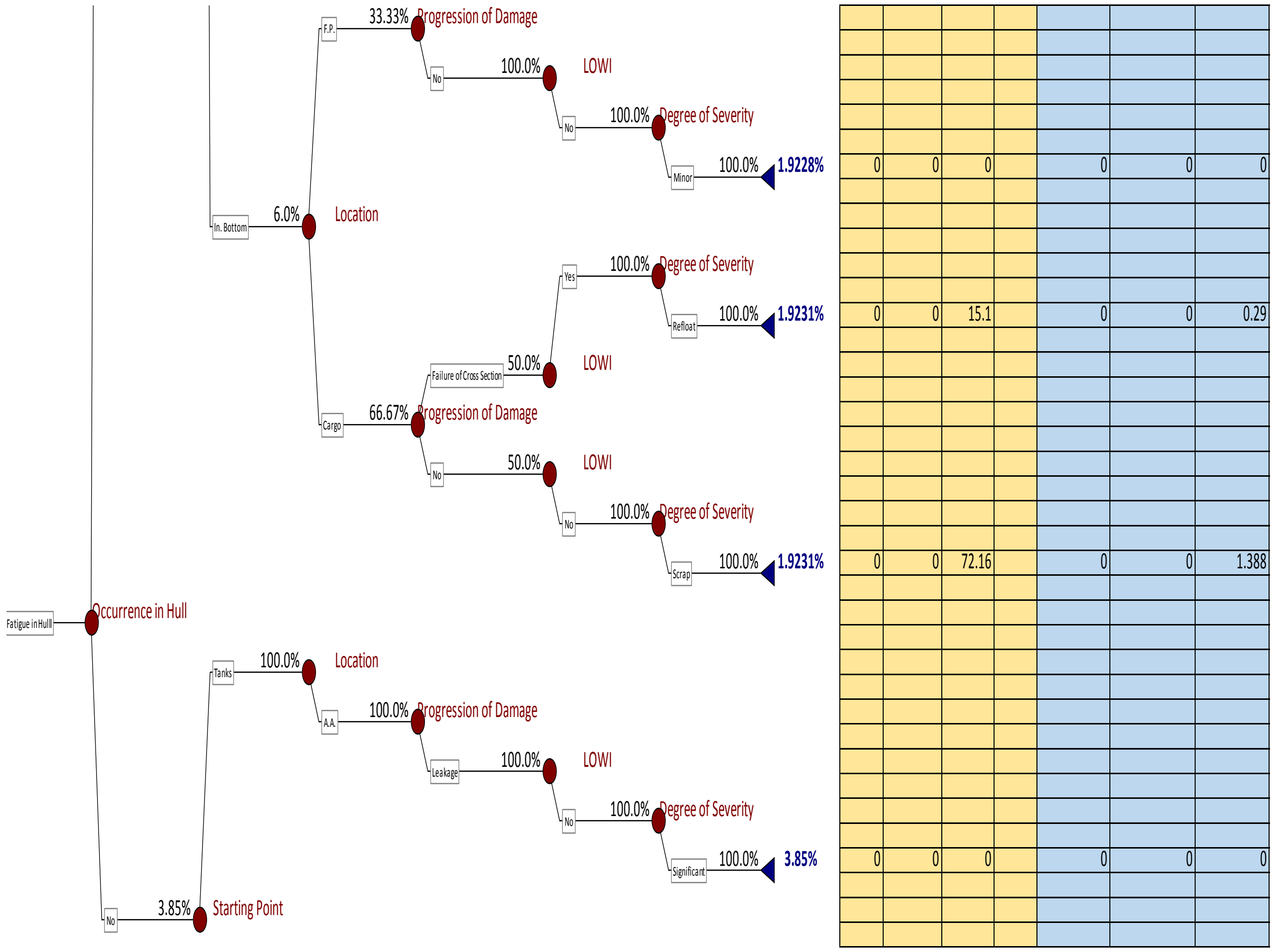


Figure B.4: Event Tree for RoPax vessels with 4,000GT and above under Fatigue failures