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Analysis of Structural Failures of General Cargo Ships

Diploma Thesis

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Contents

Table of figures

Table of tables

Abbreviations list

ALARP	As Low As Reasonably Practicable
DTS	Damage To Ship
DWT	Deadweight Tonnage
EI	Environmental Impact
EMSA	European Maritime Safety Agency
ET	Event Tree
ETA	Event Tree Analysis
FMEA	Failure Mode and Effects Analysis
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GBS	Goal-Based Standards
GT	Gross Tonnage
HAZID	Hazard Identification
HAZOP	Hazard and Operability study
IMO	International Maritime Organization
LOL	Loss Of Life
LOWI	Loss of Watertight Integrity
MAIB	Marine Accident Investigation Branch
NASA	National Aeronautics and Space Administration
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Group
PRA	Probabilistic Risk Assessment
QRA	Quantitative Risk Assessment
SWIFT	Structured What-If Technique
TA	Task Analysis
UNCTAD	United Nations conference on Trade And Development

Abstract

Despite the fact that General Cargo vessels account for roughly 17% of the world fleet, they are responsible for 42% of total ship losses, a number disproportionately higher than that of any other ship type (Butt, 2012). The cause of such alarming numbers is to be found both in the technical aspects of those ships, as well as in the business practices of their operators.

First of all, General Cargo ships are destined to carry a wide variety of goods, which means that they are not optimized to one specific type of cargo. This makes them prone to loading errors, stability and strength issues. Moreover, these vessels are usually leased for short-time periods to travel between various destinations across the world. As a result, the crew lacks time to familiarize itself with the particularities of a certain voyage.

Furthermore, many of those ships fly a convenience flag and are registered in the ports of such states. This is done as a means of receiving preferable tax treatment. On top of that, they are frequently audited by non-IACS accredited classification societies in order to avoid strict regulations concerning safety and labor issues. All of these factors account for the high numbers of accidents among these ships, compared to other, more specialized vessels. The solution to the problem lies not in eliminating this essential ship category, but rather in mitigating the technical and operative aspects that are harmful to maritime safety.

For the purpose of reducing maritime accidents and promoting maritime safety, IMO introduced a new approach to risk by adopting Formal Safety Assessment (abbreviated FSA) back in 2002 (IMO, 2002b). FSA is a carefully structured methodology for identifying potential hazards, assessing their risk, proposing options to reduce that risk, evaluating those options in terms of cost vs. benefit and proposing effective measures to minimize risks (Imo.org, 2016). Since its adoption, many such reports have been published and their propositions have served as the basis for establishing new safety regulations.

The present thesis aspires to implement the FSA approach to structural failure accidents of General Cargo ships. Structural failure accidents are those caused by either cracks or corrosion ruptures on the metallic structure of the ship and are not related to an external factor, such as collision or grounding. Contrariwise, they are caused by endogenous agents, such as the deterioration of the ship's hull due to corrosion or a poorly executed ship loading.

The method used is inspired by the second step of the FSA (Risk Analysis). Firstly, casualty data was gathered from Sea-web™ database, property of IHS Markit® corporation. Data was collected for maritime accidents that took place from January 1st, 1990 to December 31st, 2016. The vessels under investigation had a GT

lager than 150. According to their GT values, ships were classified as “small” (less than 5,000 GT) and “large” (more than 5,000 GT). Moreover, depending on the cause of the failure, accidents were categorized as “corrosion-related” or “crack-related”.

After the initial collection of 3,752 reports, careful study eliminated those that were not caused by structural failure, leaving 417 relevant incidents. The casualty reports were analyzed and parameters of interest for each accident were established in a database format. These parameters were: Place of occurrence (hull, tanks or pipes), structural point of failure (side shell, bottom shell, deck plating, etc.), location of damage (engine room, cargo space or forepeak), progression of damage, etc.

From there, statistical analysis was performed and Event Trees (ET) were constructed, highlighting all possible accident scenarios. Event Tree Analysis (ETA) is a tool for the identification and evaluation of the consequences stemming from an initial event, such as an accident. The consequences are visualized in different paths, resembling the appearance of a tree’s branches (hence the name). By assigning numerical values on each path, probability numbers for each scenario can be established (Ericson, 2005).

Moreover, consequences for each scenario were quantified. Three consequence types were recognized: loss of life, environmental pollution and damage to property. The final step was to calculate the risk value of each scenario, as the product of probability and consequence. High risk accidents were analyzed and conclusions were drawn.

Περίληψη

Παρά το γεγονός ότι τα πλοία Γενικού Φορτίου (Γ/Φ) αποτελούν περίπου το 17% του παγκόσμιου στόλου, ευθύνονται για το 42% των συνολικών απωλειών πλοίων, ένας αριθμός δυσανάλογα υψηλός σε σχέση με το πλήθος τους, αλλά και σε σύγκριση με αντίστοιχα ποσοστά άλλων τύπων πλοίου (Butt, 2012). Το φαινόμενο αυτό οφείλεται τόσο σε τεχνικά αίτια, όσο και σε παράγοντες που σχετίζονται με το ευρύτερο καθεστώς λειτουργίας των πλοίων Γ/Φ.

Αρχικά, ο σκοπός ενός πλοίου Γ/Φ είναι να μεταφέρει μια πληθώρα αγαθών διαφορετικού τύπου, που σημαίνει ότι τα πλοία αυτά δεν είναι εξειδικευμένα στη μεταφορά ενός συγκεκριμένου τύπου φορτίου. Αυτό τα καθιστά επιρρεπή σε σφάλματα κατά τη φόρτωση, ενώ μπορεί ακόμη να θίξουν την ευστάθεια και την αντοχή της κατασκευής. Σε επιχειρησιακό επίπεδο, τα πλοία αυτά δραστηριοποιούνται στην αγορά spot, δηλαδή ναυλώνονται για σχετικά μικρή διάρκεια και σε ταξίδια μεταξύ διαφόρων προορισμών ανά τον κόσμο. Αυτό δημιουργεί αδυναμία στο πλήρωμα να εξοικειωθεί με τις ιδιαιτερότητες ενός συγκεκριμένου ταξιδιού, τα μορφολογικά χαρακτηριστικά της περιοχής, κτλ.

Επιπρόσθετα, πολλά πλοία Γ/Φ πλέουν κάτω από σημαίες ευκολίας και είναι νηολογημένα σε λιμένες τέτοιων κρατών για λόγους ευνοϊκότερης φορολογικής και νομοθετικής αντιμετώπισης. Δεν είναι σπάνιο για τέτοια πλοία να ελέγχονται από υποδεέστερους νηογνώμονες που δεν ανήκουν στον IACS προκειμένου να αποφύγουν την υιοθέτηση αυστηρών κανόνων ασφαλείας και εργασίας. Τα παραπάνω αίτια συμβάλλουν στον αυξημένο αριθμό ατυχημάτων που εμφανίζουν τα πλοία Γ/Φ συγκριτικά με άλλους τύπους πιο εξειδικευμένων πλοίων. Η λύση στο πρόβλημα έγκειται, όχι στην εξάλειψη αυτής της αναγκαίας κατηγορίας πλοίων, αλλά στη θεραπεία των παραγόντων εκείνων που βλάπτουν την ασφάλεια στη θάλασσα.

Προκειμένου να μειωθεί ο αριθμός των ατυχημάτων και να εδραιωθεί η ναυτική ασφάλεια, ο Διεθνής Ναυτιλιακός Οργανισμός (International Maritime Organization – IMO) εισήγαγε μια νέα μέθοδο προσέγγισης του ρίσκου, υιοθετώντας από το 2002 τη μέθοδο Formal Safety Assessment (FSA) (IMO, 2002b). Η FSA είναι ένα αυστηρά δομημένο εργαλείο για την αναγνώριση των πιθανών κινδύνων, τον υπολογισμό του ρίσκου που απορρέει από αυτούς τους κινδύνους, την παράθεση προτάσεων μείωσης του ρίσκου, της αξιολόγησης των προτάσεων αυτών σε όρους κόστους-ωφέλειας και τέλος της παροχής αποτελεσματικών προτάσεων μείωσης του ρίσκου (Imo.org, 2016). Από την περίοδο εμφάνισής της μέχρι σήμερα έχουν εκπονηθεί πολυάριθμες μελέτες και έχουν δημοσιευτεί πολυάριθμες εκθέσεις των οποίων οι προτάσεις αποτέλεσαν τη βάση για την καθιέρωση νέων κανονισμών ασφαλείας.

Σκοπός της παρούσας εργασίας είναι η εφαρμογή της μεθόδου FSA σε ατυχήματα που οφείλονται σε δομικές αστοχίες πλοίων Γ/Φ. Με τον όρο δομικές αστοχίες ορίζονται οι αστοχίες εκείνες της μεταλλικής κατασκευής του πλοίου που οφείλονται σε θραύση ή διάβρωση και δεν σχετίζονται με κάποιο εξωτερικό παράγοντα, όπως για παράδειγμα μια σύγκρουση ή προσάραξη. Αντιθέτως, οφείλονται σε ενδογενή αίτια, όπως είναι η αλλοίωση της επιφάνειας της γάστρας λόγω διάβρωσης είτε η αστοχία λόγω λανθασμένης φόρτωσης.

Ως μέθοδος εργασίας έχει επιλεγεί το 2^{o} βήμα της FSA (Ανάλυση Ρίσκου). Αρχικά, συγκεντρώθηκαν στοιχεία ατυχημάτων από τη βάση δεδομένων Sea-web™ της εταιρείας IHS Markit®. Τα δεδομένα αφορούν ατυχήματα που συνέβησαν από τη 1^{η} Ιανουαρίου του 1990 μέχρι τη 31^{η} Δεκεμβρίου του 2016. Τα υπό διερεύνηση πλοία έχουν ολική χωρητικότητα μεγαλύτερη των 150 κόρων. Με βάση την ολική χωρητικότητα, τα πλοία χωρίστηκαν σε ‘μικρά’ (ολική χωρητικότητα μικρότερη των 5,000 GT) και μεγάλα (ολική χωρητικότητα μεγαλύτερη των 5,000 GT). Επίσης, ανάλογα με το αίτιο της αστοχίας, τα ατυχήματα κατηγοριοποιήθηκαν σε ‘οφειλόμενα σε διάβρωση’ και ‘οφειλόμενα σε θραύση’.

Μετά την αρχική συλλογή 3,752 αναφορών ατυχημάτων, λεπτομερής μελέτη οδήγησε στον αποκλεισμό όσων δεν σχετίζονταν με δομικές αστοχίες, αφήνοντας 417 έγκυρα ατυχήματα. Οι αναφορές μελετήθηκαν λεπτομερώς και θεσπίστηκαν παράμετροι ενδιαφέροντος σχετικές με τα ατυχήματα, όπως: Κατηγορία δομικού στοιχείου υπό αστοχία (γάστρα, δεξαμενές, σωληνώσεις), τμήμα υπό αστοχία (πλαϊνό έλασμα, έλασμα πυθμένα, έλασμα καταστρώματος, κτλ.), τοποθεσία αστοχίας (μηχανοστάσιο, χώρος φορτίου, πρωραίο τμήμα), τον τοπικό ή μη χαρακτήρα της αστοχίας, κλπ.

Εν συνεχεία, πραγματοποιήθηκε στατιστική ανάλυση και κατασκευάστηκαν Δέντρα Γεγονότων (Event Trees), στα οποία περιλήφθηκαν όλα τα πιθανά σενάρια ατυχημάτων. Το Event Tree Analysis (ETA) είναι μια μέθοδος για την αναγνώριση και τον αριθμητικό υπολογισμό των συνεπειών που απορρέουν από ένα αρχικό γεγονός, όπως η εκδήλωση ενός ατυχήματος. Οι πιθανές πορείες διάδοσης του ατυχήματος απεικονίζονται ως διαφορετικοί κλάδοι του δέντρου (εξ’ ου και η ονομασία). Αντιστοιχίζοντας αριθμητικές τιμές σε κάθε κλάδο προκύπτουν οι συνολικές πιθανότητες πραγματοποίησης κάθε σεναρίου (Ericson, 2005).

Επιπρόσθετα, για κάθε σενάριο ποσοτικοποιήθηκαν οι συνέπειες αυτού. Οι συνέπειες είναι τριών ειδών: απώλεια ανθρώπινης ζωής, περιβαλλοντική μόλυνση και απώλεια περιουσίας. Τέλος, υπολογίστηκε το ρίσκο κάθε σεναρίου, ως το γινόμενο της πιθανότητας υλοποίησής του επί την αριθμητική τιμή των συνεπειών αυτού. Τα σενάρια με τις υψηλότερες τιμές ρίσκου αναλύθηκαν και εξήχθησαν συμπεράσματα.

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1. Introduction

1.1 The problem

Firstly highlighted by Russia to IMO in 2006, General Cargo vessel safety is a highly concerning issue. Specifically, despite of the fact that General Cargo ships represent only about 17% of the world fleet, they account for 42% of total ship losses and –more disturbingly- for more than 1 in 4 fatalities throughout the maritime industry (27%) (period 1999-2004). In addition, they appear to have the second highest rate of port state control inspections with deficiencies (60% for General Cargo ships versus 54% for other ship types) and detentions (8% for General Cargo ships, 6% for other ship types) (Chrysavgis, 2011).

The same trend appears to hold true for more recent statistics as well. According to the *Annual Overview of Marine Casualties and Incidents 2016* published by EMSA, General Cargo ships steadily appear to have the largest percentage of accidents among cargo ships for the years 2011 to 2015. Specifically for the year 2015, 33% of cargo ship casualties involved General Cargo vessels, followed by containerships with 17%, almost half the frequency of the previous category (EMSA, 2016).

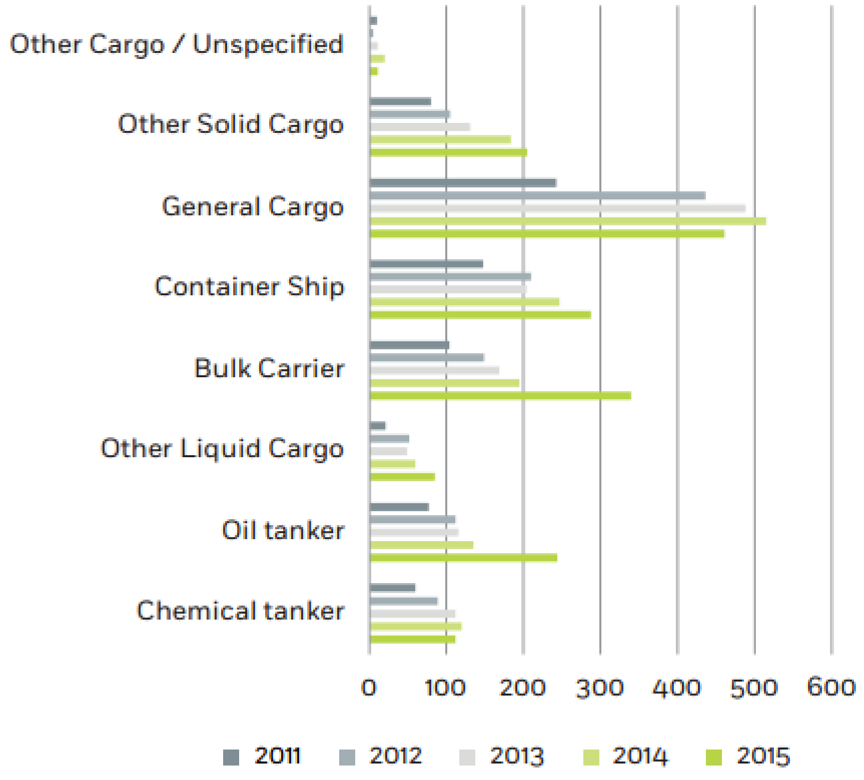


Figure 1: Number of accidents per ship type, per year (EMSA 2016)

EMSA reports are not inclusive of all ships registered in the world fleet. Data is collected for incidents that:

- Involve ships that fly the flag of an EU Member State,
- Occur in Member State's waters
- Involve interests of the Member States

The above criteria clearly limit the number of ships under consideration and thus render the statistics less representative of the world fleet. According to UNCTAD's *Review of Maritime Transport 2016*, ships flying an EU Member State's flag comprise roughly 15% of the world fleet in number of vessels. The vast majority of ships are registered outside EU, most likely for reasons of preferable tax treatment, and to avoid strict labor and environmental regulations imposed by developed nations. It is safe to assume, however, that the landscape is not much different on a global level.

A review by Southampton Solent University studied shipping accidents for the period of 1997 to 2011 and found that "General Cargo vessels account for nearly 50% of all vessel types lost at sea for the research timeframe" (Butt, 2012).

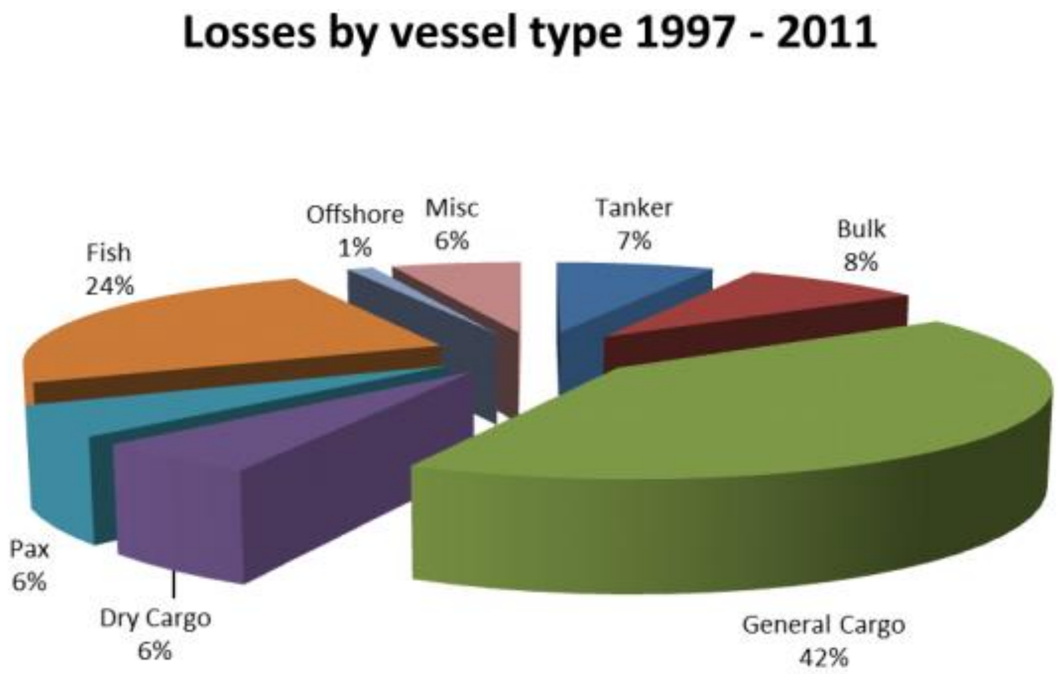


Figure 2: Percentage of losses by vessel type for the period 1997-2001

The same review stated that General Cargo/multi-purpose vessels was by far the most commonly detained ship type, with 90%, 84% and 72% for the years 2009, 2010 and 2011, respectively.

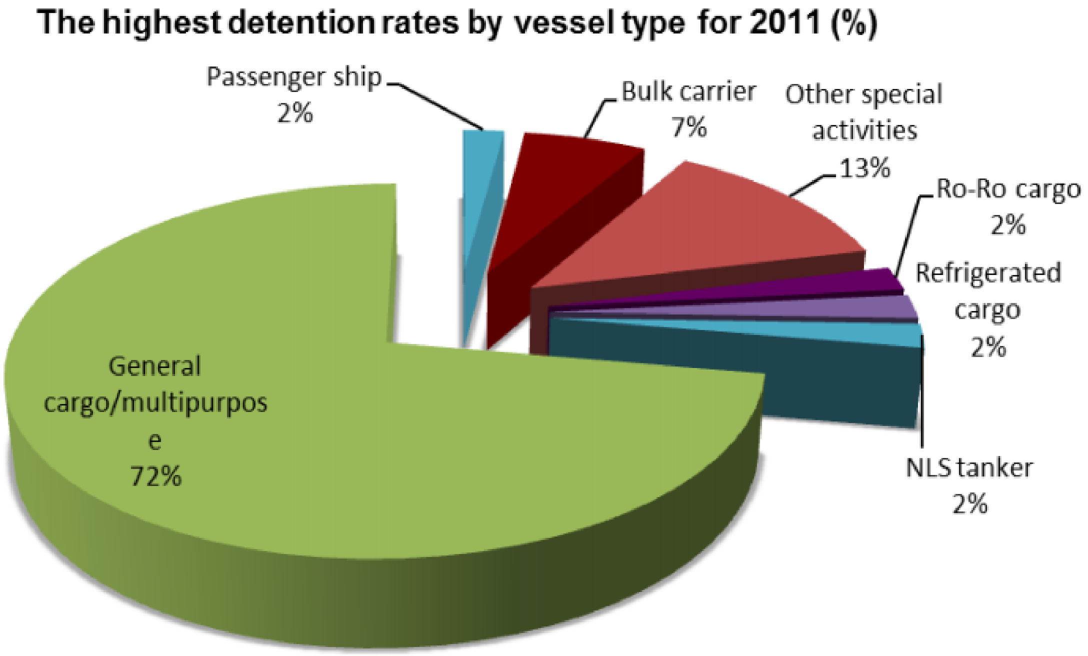


Figure 3: Detention rates by vessel type for 2011

In 2012, a publication by IMO stated *'Most of the recorded accidents involved General Cargo ships'* (IMO, 2012).

The above evidence clearly emphasizes that attention must be given to the direction of General Cargo ship safety. Before anyone attempts to make changes in the direction of mitigating any issue, sufficient analysis of the current situation must be performed.

1.2 Thesis structure

The thesis is divided into 9 chapters. The first chapters (1 to 6) provide a thorough understanding on the prerequisite knowledge needed for chapters 7, 8 and 9; were the research process and its results are described. The material is laid out in a logical order for the purpose of facilitating comprehension of the subject for even the non-initiated reader.

Chapter 1 is the introductory chapter which describes the main incentive, which is the great disparity between accidents of General Cargo ships in comparison with other ship types. By providing established reports the author makes a case that indeed the problem exists and that the need for a solution is imperative.

Chapter 2 provides an introduction to Risk Analysis, focusing on two main subjects: What is risk analysis and how it evolved throughout the years, providing references to milestone events that have helped shape today's landscape of Risk Analysis and especially that of Probabilistic Risk Assessment (PRA); which is the backbone of FSA. By explaining the history of risk analysis the reader understands the motives behind its use and the events that have helped shape it.

Chapter 3 revolves around the General Cargo ship. It provides information about its role in the maritime industry and highlights its basic design features that establish this distinct ship type. Basic knowledge of the layout of General Cargo ships is deemed essential for the later understanding of the failure mechanisms that take place.

Chapter 4 describes the causes of structural failures, namely corrosion and cracking. Insight is given in the mechanics of such phenomena in order to help shape a more complete image of what will be studied later.

Chapter 5 is about the notion of risk described from a mathematical perspective. Essential to the understanding of risk is the concept of probability, which is a mathematical tool used to model uncertainty. Due to the fact that real-life problems can make little use of the probability as it is described in its pure axiom form, the notion of frequency has to be introduced. Frequency is a statistical tool based on observation that under certain circumstances provides a good estimation of the respective probability.

Chapter 6 introduces Formal Safety Assessment (FSA), a tool used by the International Maritime Organization (IMO) to support the decision-making process for establishing new safety regulations for ships. FSA is a structured method for performing risk analysis and management. Since the thesis is heavily influenced by the FSA methodology, the inclusion of this chapter was deemed necessary.

Chapter 7 introduces the reader to the essence of the thesis, which is a statistical analysis of General Cargo ship accidents caused by structural failures. The research process is laid out in a step-by-step fashion. At first, the Sea-web™ casualty database is presented, along with its capabilities. Subsequently, ships are classified into categories by Gross Tonnage (GT) and cause of failure (corrosion/crack). Parameters of interest are selected and the creation of the ET is realized. Finally, the process of probability assessment and quantification of consequences (in terms of lives lost, environmental impact and damage to property) is described.

Chapter 8 cites the results of the analysis. Both a general outlook and a detailed approach are included. The general outlook provides a broad insight into the factors that characterize General Cargo ship accidents, such as the geographical area where the incidents occurred, the time in the day, the type of environment (port/harbor, open sea), weather conditions in the area, etc. The detailed study of the accidents provides further information, by classifying the ships into different categories and examining parameters such as the cause of the accident (corrosion/crack), the structural member under damage (deck plating, side shell, etc.) the progression of the damage, the outcome, etc. The results are then compared by the use of visual representation techniques, such as bar charts, pies and tables. Conclusions can easily be drawn by such representations.

Chapter 9 is the final chapter, in which conclusions are summarized and suggestions for further study are given. A review on FSA is performed, depicting the methods advantages, disadvantages and limitations. Finally, possible future developments and suggestions for further study are mentioned.

2. Literature review

2.1 The beginning of Risk Analysis

Uncertainty is a fact of life. For every action taken there is a certain amount of uncertainty that accompanies it. Since the dawn of mankind, humans have been trying to predict -and even change- the future in an effort to fight uncertainty.

The earliest signs of risk analysis can be traced back to Mesopotamia in 3200 BC (Covello & Mumpower, 1985). Whenever people had a risky venture to undertake (such as the choice of spouse or a major business decision), they would consult the Asipu. The Asipu tribe would consider all the important aspects of the problem at hand, identify possible paths of action and even collect data on the likelihood of each outcome. They would then carve a tablet -a 'report'- on which they would recommend the most favorable alternative. The process relied primarily on religious signs from gods and less in logic and mathematics. However, it can be considered a primitive form of risk analysis, presenting many similarities with modern day methods.

Even though risk analysis started in Mesopotamia, it wasn't until the emergence of the probability theory in 17th century that the field took a form more closely resembling that of modern risk analysis.

2.2 Nuclear Industry

In the late 1960s and 1970s, nuclear power plants were on the rise in the US (Keller & Modarres, 2005). Since then, nuclear energy had never been used for such a benign purpose except from warfare. Having experienced the terror of the atomic bombs in WWII, the world became increasingly concerned about the safety aspects of harvesting nuclear power. Public demand led to a number of independent studies –often contradicting- which did little to none in terms of providing a sound argument for or against the operation of such plants.

In 1972, the first complete study using Fault Tree and Event Tree Analysis was conducted by a team of experts from academia, industry and government. It was called the WASH-1400 study (or RSS-Reactor Safety Study). The report was eventually published in 1975. Both the analytical tools used in this study, as well as the philosophy as a whole, closely resembled what today is called 'Probabilistic Risk Assessment'. It was the first practical application of PRA.

The report generated a storm of criticism after its publishing. Due to the results of the study, which assessed the safety of nuclear plants to be lower than what was circulating at the time, the study became the subject of political controversy. As a result, the newly introduced methodology was not immediately embraced. The method used back then was based on deterministic analysis and to the engineering community PRA seemed profoundly inferior.

It was only after another accident took place that the PRA methodology, firstly introduced in the WASH-1400 study, was put back into examination. The Three Mile Island reactor meltdown in March 1979 was caused by events not included in the formal documentation of the time, thus current approaches to reactor safety were proven insufficient. The RSS study –on the other hand- included this specific accident scenario, even though it did not rank as a significant one.

The Three Mile Island incident showcased that minor events are capable of leading up to a major disaster. According to the approach of the time, only large failures were used as a design basis, completely ignoring the fact that many small incidents can contribute to a severe accident. PRA methodology took every conceivable failure into account, thus providing a more holistic and reliable approach to safety. It is worth noting that the 1974 study warned about the dangers tsunami waves can impose to reactors close to shore, much like it happened in Fukushima power plant in March 2011.

Having failed as a methodology, deterministic analysis lost to PRA. For the following years up to date, PRA is the main way of work for safety assessment in the nuclear industry.

In the following years, the nuclear industry adopted PRA as the main analytical tool for assessing safety, since 'both the U.S. Nuclear Regulatory Commission (NRC) and the nuclear industry have recognized that probabilistic risk assessment (PRA) has evolved to be more useful in supplementing traditional engineering approaches in reactor regulation' (U.S.NRC, 2003). This is clear from the number of succeeding reports published, all of which utilize PRA. Some notable ones among them, are:

- CRAC II report (officially named NUREG/CR-2239) published in 1982

- NUREG-1150 report in 1990

PRA methods used in this study were better suited to deal with uncertainties and low frequency events.

- SOARCA (State-Of-the-Art Reactor Consequence Analysis or NUREG-1935) in 2012

Although the use of deterministic modelling is dominant, the use of PRA is still extensive, especially in determining significant accidents for later processing.

2.3 Chemical Industry

The chemical and process industry started implementing the PRA methodology in the late 1970s, in which case it was named *Quantitative Risk Assessment* (QRA). A series of accidents triggered authoritative bodies to implement measures towards mitigating the threats. The following events led to the establishment of QRA as a standard tool for risk evaluation:

- Flixborough (UK) disaster in 1974, where 28 people were killed and 36 seriously injured due to vapor cloud explosion
- Seveso (Italy) accident in 1976, due to toxic gas cloud. Fortunately, no deaths were reported. However, the long-term health effects of nearby residences were significant.
- Bhopal (India) gas tragedy in 1984 was by far the most severe accident. At least 3,800 people lost their lives due to a toxic gas cloud. The figures cannot be verified, but the actual death toll is estimated close to 15,000 over the years; as a result of exposure to the pollutant factor (methyl isocyanate)
- San Juanico (Mexico) disaster in 1984, where a vapor cloud explosion killed 650 people, while severely injuring approximately 6,000.

Due to the Seveso disaster, the European Union decided to pass "Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances", commonly known as the Seveso Directive. According to this law and its amendments (Seveso I (1982), II (1996) and III (2015)), safety reports ought to be prepared for the operations of processing establishments. The way in which such reports should be made opened the way for the introduction of QRA (Kirchsteiger, Christou & Papadakis, 1998).

2.4 Offshore Industry

In July 1988, a North Sea oil production platform called *Piper Alpha* exploded, killing 167 people and leaving 3.4$ billion in damage. The platform accounted for almost 10% of North Sea's oil and gas production and the incident was declared "the worst disaster in the offshore industry".

Public inquiries were made under Lord Cullen (Justice General) and in 1990, the *Lord Cullen Report* was published. It was divided into two parts, with the second part proposing changes that had to be made in the offshore industry in order to reduce the risk of major accidents. One of the changes was the obligation of the operator to produce a safety case in order to prove that the facility is safe to operate. The tool needed for such an assessment to be carried out was QRA. This opened the way for the introduction of QRA into the offshore industry. By November 1995, the safety case for every offshore operator in UK waters had been mandatory by the Health and Safety Executive (HSE) body in UK (Kontovas, 2005).

2.5 Shipping Industry

The shipping industry was the last one to adopt the PRA methodology. This was in part due to the fact that shipping is not deemed as a 'high risk' industry, like chemical processing or nuclear factories.

A series of serious accidents in the late 1980s, most notable of which was the capsize of *Herald of Free Enterprise* (1987), which led to 193 deaths and highlighted the need for reformations on maritime safety (Kontovas, 2005). Under such conditions, Lord Carver ordered an investigation to be carried out. The report on the inquiry showcased that a more scientific approach to ship safety should be taken by adopting a performance-based approach. Soon after, the UK Maritime and Coastguard Agency responded by proposing the use of Formal Safety Assessment (FSA) to the IMO, a more proactive and scientific tool to assess risk that relies heavily on PRA. IMO welcomed the new approach to risk by publishing guidelines for its implementation (IMO, 2002b). From 2002, FSA is in use as a supportive tool for decision-making for safety-related issues. It provides a proactive and holistic approach to maritime risk, by combining engineering, as well as the human factor in its calculations.

Until today, a number of FSA reports has been published for different types of vessels, such as:

- Bulk carriers (IMO, 2002a)
- LNG carriers (IMO, 2007a)
- Container vessels (IMO, 2007b)
- Crude oil tankers (IMO, 2008a)
- Cruise ships (IMO, 2008b)
- RoPax ships (IMO, 2008c)
- General Cargo ships (IMO, 2010c)

FSA reports are not necessarily performed on specific ship types. They might be related to a more or less specific aspect of the ship's operation. For instance, independent FSA reports for life saving appliances and navigation equipment also exist.

Unfortunately, reforms and advances in legislation are almost always motivated by serious disasters that receive wide public coverage. This is so, due to lack of motives provided to operating companies to act upon something in advance. It is less costly to adopt a passive attitude towards risk than it is to make changes in advance. This mentality, primarily driven by the need to cut expenses leads to the loss of human lives, environmental pollution and eventually monetary expenses later on.

3. The General Cargo ship

General Cargo vessels are ships designed to carry a wide variety of dry cargoes, either unitized (such as vehicles, machinery, etc.) or in bulk (such as grain, cement, etc.) (Siwertell.com, 2016). Their ability to handle a wide mix of cargoes makes them extremely versatile and indispensable to the world trade (Maritimeinfo.org, 2016). Despite design progress and technological advancements, their basic form has been around since 1860s making them the oldest cargo vessel type in existence.

The versatility of cargo and their smaller size -when compared to other ship types- means that these ships can transfer cargo from and to multiple parts of the world, making them ideal for the spot market (Marine Insight, 2017). In addition, many of them have on-board handling machinery (cranes, etc.) which makes it possible to visit smaller ports that lack infrastructure and are inaccessible to larger liner vessels.

Figure 4: Many General Cargo vessels carry their own cargo handling equipment.

According to size, General Cargo vessels can be categorized in the following classes (En.wikipedia.org, 2016a):

- Handy size ships
  The smallest class and weight between 28,000 and 40,000 DWT.

- Handymax ships
  These ships can weigh between 40,000 and 50,000 DWT.

- Panamax
  This class represents the maximum ship dimensions that can pass through the Panama locks (max. length: 294m, max. width: 33.5 m, max. draft: 12 m). This roughly translates in a weight between 60,000 and 80,000 DWT.

Though there are larger classes -such as Aframax and Suezmax- it's a rare sight for General Cargo vessels to be built in such dimensions due to the nature of their task and the market in which they operate. Should the need for larger carriers rises, more specialized vessels and port facilities are used.

Other categorizations must be done using different criteria besides ship size. For example:

- According to cargo gear they can be divided into ships with or without cargo gear.
- According to the area in which they operate, ships are categorized into coastal liners and sea-river vessels (En.wikipedia.org, 2016b).

When it comes to design specifications, cargo space is the main area of interest. A typical cargo space extends from side-to-side and is confined by the side platings which are welded on the ship's frames. No longitudinal bulkhead is present. As to its length, it extends between two transverse watertight bulkheads. Those bulkheads can be constructed in two forms:

- By the use of a bulkhead plate with welded stiffeners at equal distances for reinforcement.
- Corrugated bulkheads. They are most commonly used in modern vessels since they provide a better strength to weight ratio than traditional stiffeners (Karydis, 2000).

It's not uncommon for General Cargo vessels to have a uniform cargo space without any intermediate watertight bulkheads. In this case the cargo area is confined by the engine room bulkhead in the back and the collision bulkhead in the front.

In order to maximize cargo storage efficiency, movable bulkheads are also utilized, subdividing the cargo space into two or more holds. The water tightness for these bulkheads however is not sufficient and are only used as a means of space allocation (Macgregor.com, 2016).

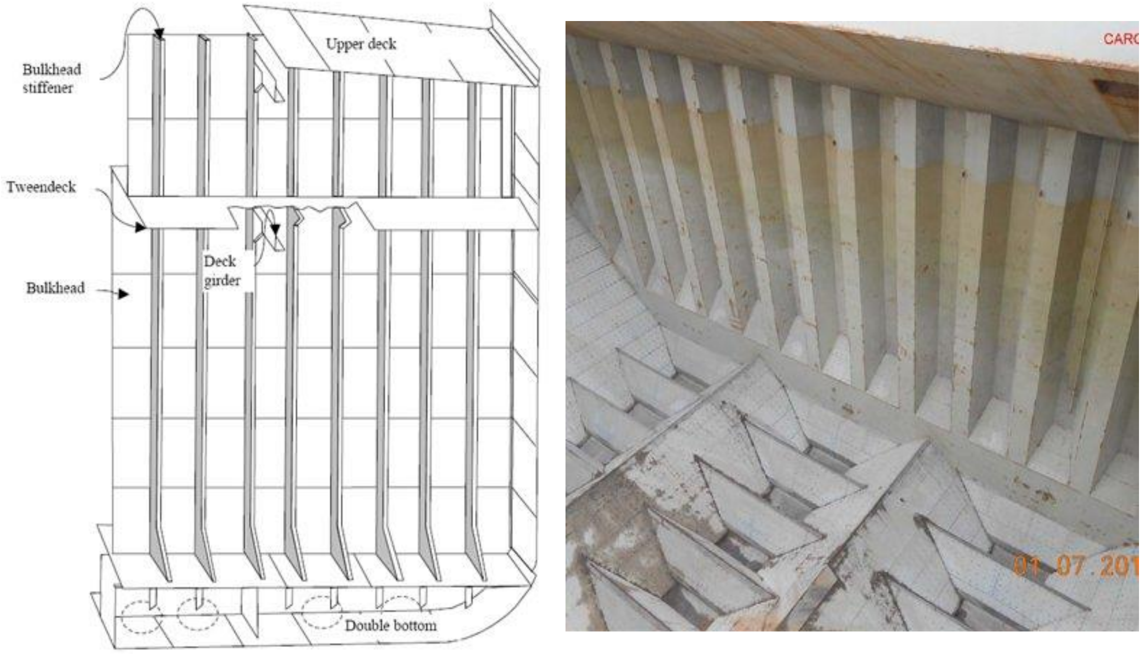


Figure 5: Two different types of bulkheads. Left: Older type consisting of a plate with welded stiffeners. Right: Modern type corrugated bulkhead. This type provides superior strength and torsional rigidity.

The hold's bottom is usually double. This is done as a measure to prevent pollution in an event of collision or running aground, as well as a mean of longitudinal reinforcement. It is constructed by two plates (the bottom plating and the inner bottom plating) with stiffeners and girders running in the longitudinal and transverse direction. The girders are holed so that pipes and other systems can run along, and to facilitate maintenance/repair activities (manholes) (Karydis, 2000).

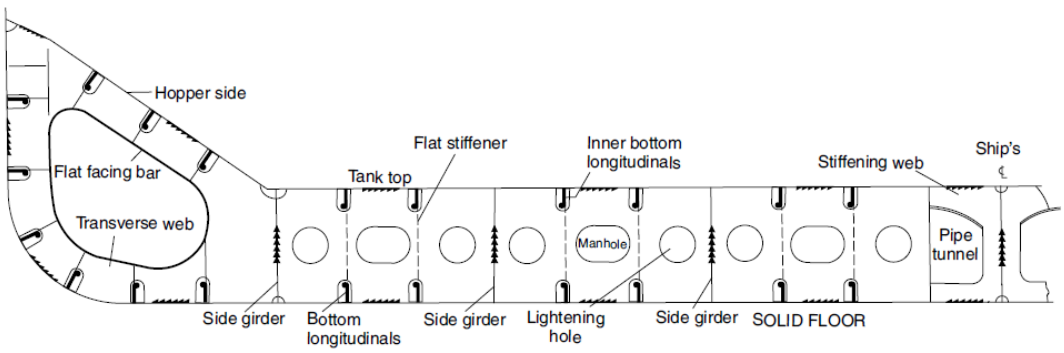


Figure 6: A typical double bottom cross section.

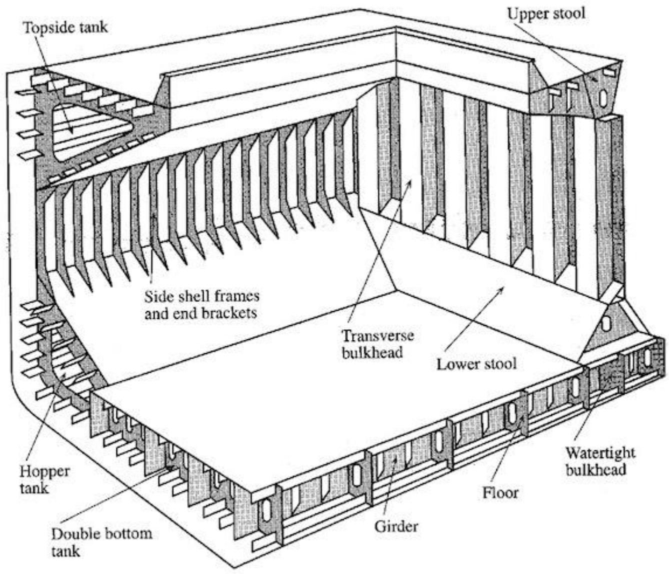
At the top, the cargo space is confined by the deck plating, reinforced with stiffeners. Large openings on the top, called hatch openings, allow for the hatch covers to slide. The hatch cover lays on top of the hatch coaming, vertical plates along the perimeter of the opening that prevent water entry and act as a stool where the rails for the hatch cover are placed.

Hatch covers come in a variety of types, with different opening mechanisms to accommodate different needs. Some categories are:

- Lifting type
- Rolling type
- Folding type
- Sliding type

Each of these categories can be further subdivided. All of the above types can be met in a General Cargo vessel, though the lifting type is less common in General Cargo vessels (Sinha, 2016).

Finally, the double-bottom and the upper-corner space where the side shell meets the deck plate are used as ballast tanks (topside tanks). Other locations might be



used instead or in addition to these, but they are not common. A drawing of a typical cargo hold is depicted.

Figure 7: A typical cargo hold found in most dry-cargo vessels. Notice the ballast tanks on the top and bottom sides, as well as the double bottom tank.

Though one can go into greater detail in describing the structure of a General Cargo vessel, the purpose of this passage is to provide the essential information needed for the reader to understand the basics of General Cargo ships in order to comprehend the chapters ahead.

4. Structural Failures

4.1 Corrosion

Most materials interact with their environment in ways that impair their original qualities. For instance, prolong exposure of polymers in UV radiation –such as sun exposure- leads to degradation. A similar process happens to ceramic materials in high temperatures or extreme environments. In the case of metals, deterioration is realized either by dissolution (corrosion) or by the formation of a non-metallic surface layer (oxidation).

Corrosion in metals is defined as the electrochemical process by which the chemical structure of the surface is altered to a more stable form.

Estimations show that the maritime industry alone spends between $50-80 billion each year in measures to prevent and fix corrosion-related issues (LMI, 2006). As a result, great emphasis is being given to corrosion prevention methods.

When it comes to ships, corrosion by sea water (aqueous corrosion) is the most prevalent form met, since a large portion of the hull is permanently submerged in the sea. The contact between metal and sea water leads to transfer of electrons from one chemical to the other. Specifically, the metal loses electrons out of its outer layer, forming positively charged ions. The ions dissolve into the water and the free electrons react with oxygen (O_2) and water (H_2O) to form hydroxide ions (OH^-). These hydroxide ions react with the positive metal ions and form oxides, known as rust (Chem1.com, 2016).

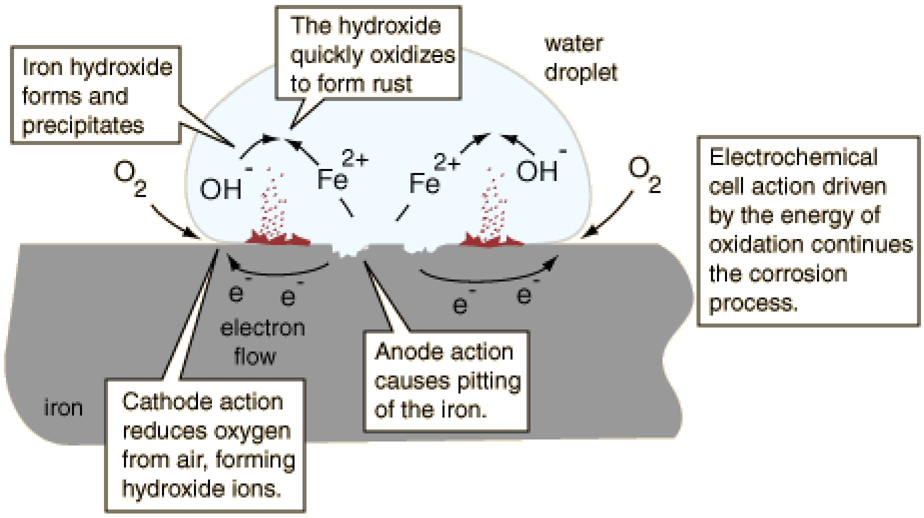


Figure 8: A diagram of the chemistry of the corrosion process.

Rust is a more stable substance in comparison to the original metal, meaning its in a lower energy state. However, it presents inferior strength characteristics.

Substitution of the metallic structure with rust makes the structure thinner and more susceptible to damage due to stress.

Figure 9: A ship's hull affected with rust. Extensive corrosion deteriorates the metal structure and can cause strength issues.

4.1.1 Types of corrosion

Although the mechanism behind corrosion is electrochemical reactions driven by the laws of chemistry, the physical forms in which it can manifest itself are practically endless. In engineering practice, it is useful to categorize corrosion into types, according to the morphology of the corroded environment. The following categories are the ones most commonly met in the context of maritime structures (Callister & Rethwisch, 2010). It is not deemed purposeful to overanalyze types but rather explain them in brief, since it is out of the scope of this study.

- Uniform corrosion

Uniform corrosion is the most common form of corrosion. The electrochemical reaction manifests itself with equal intensity across the entire surface of the material. Its characteristics -such as the rate of corrosion- can be easily predicted and thus designed against it. Examples of this type of corrosion include the general rusting of iron when exposed to humid environments.

- Galvanic corrosion

Galvanic corrosion is caused when two metals with different compositions are in contact under an electrolytic environment, such as sea water. In this case, the reactive metal will corrode, while the more inert metal (noble) will stay intact.

During this reaction, electrons flow from the inert (called the cathode) to the reactive metal (called the anode). Due to electric charges being transferred, electrical current occurs and the reaction is characterized as “electrochemical”. The corrosion process depends on the difference in “nobility” of the metals, the ratio of their surfaces and the conductance of the electrolytic solution.

Corrosion is not always an unwanted phenomenon. For instance, galvanic corrosion is widely used in sea-going vessels and other marine constructions in order to prevent the hull from deteriorating due to saltwater. By placing cathodic protection systems on the hull’s surface, the ship structure acts as a cathode, while the anode (usually a small rounded piece of anodic metal) takes the effects of the corrosion.

- Pitting corrosion

This type of corrosion results in the creation of metal holes -called pits- of various diameters. The density of the pits can also vary: they can be close together or isolated. Usually, corrosion products (such as rust) cover the pits. Pitting corrosion is more dangerous than uniform corrosion, due to the fact that it is more difficult to predict and detect.

The process is caused due to poor coating application, presence of non-uniformities in the metallic surface (such as inclusions) or by water characteristics, such as acidity, high chloride concentrations, etc. With a portion of the protective layer gone, metal is directly exposed to the corrosive environment.

As the metal recedes, the structure becomes thinner and non-uniform. As a result, stress concentrations might occur in areas under pitting corrosion. This can activate Stress Corrosion Cracking mechanism (SCC) in the pits, leading to catastrophic results. More information on SCC in the subsequent pages.

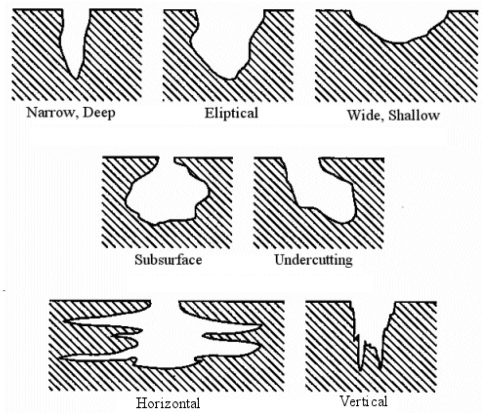


Figure 10: Pitting corrosion on the surface of steel (left) and different methods of propagation of the pits (right).

- Crevice corrosion

Crevice corrosion occurs in shielded areas, such as contact areas between parts, openings and seams. The affected area is close to the joining surfaces. It is caused by a difference in ions concentration between the two materials.

This type of corrosion can be prevented by using welded instead of riveted joints and removing accumulated deposits of electrolytes (such as sea water).

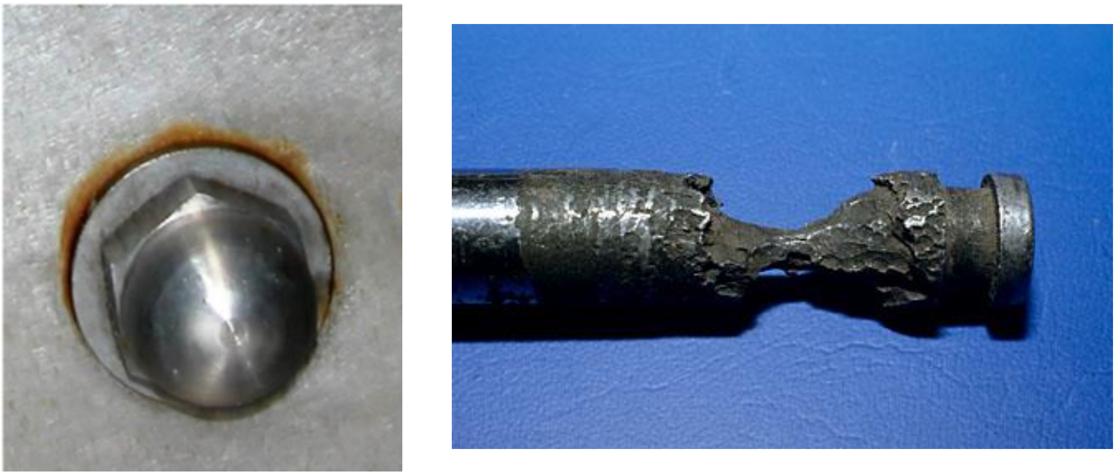


Figure 11: Crevice corrosion is usually observed in joined surfaces, such as the area around a washer nut.

- Erosion-corrosion

Erosion-corrosion is the combination of electrochemical corrosion and mechanical wear that stems from the fluid's motion around a metal surface. The rate of corrosion increases with the speed of the flow. Most corrosion types met in ships include erosion as well, since they involve moving liquids around solid metal surfaces. For example, the flow of water through a piping system, the flow around

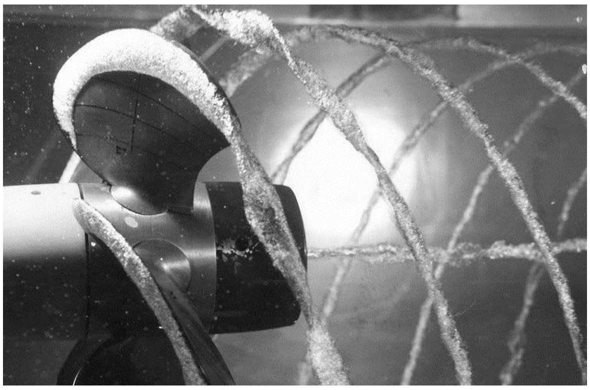


Figure 12: Cavitation is a form of erosion-corrosion met on ships.. It is an extremely dangerous phenomenon that can destroy the propeller's surface.

a ship’s hull, cavitation on the propeller’s edges are phenomena where erosion manifests itself.

- Selective leaching

Selective leaching (also called dealloying) is met in solid solution alloys. It occurs when one element of the alloy is removed by corrosion, while the other elements remain intact. It impairs the mechanical and physical properties of the material. The mechanism of selective leaching is that of a small scale galvanic corrosion between the boundaries of each individual material within the alloy. The most common example is the dezinfication of brass.

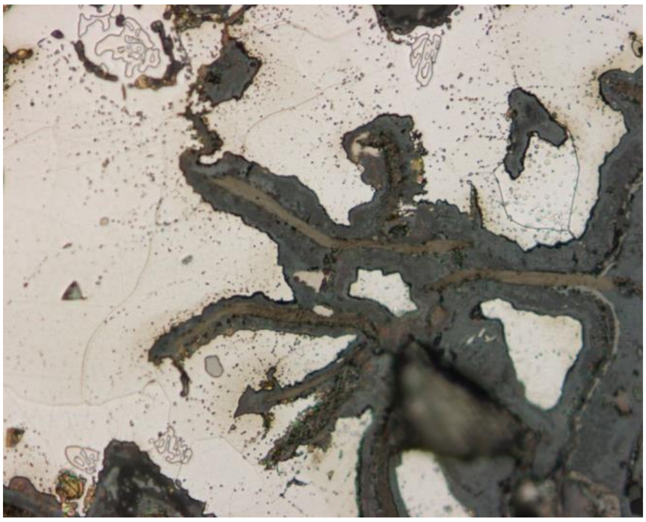


Figure 13: Dealloying of cast iron (500x)

- Intergranular corrosion

This type of corrosion attacks the grain boundaries of metallic alloys. It is commonly met in stainless steels when heated between 500°C and 800°C for sufficient time. This causes chromium carbide particles ($Cr_{23}C_6$) to form along the grain boundaries. This region is prone to corrosion.

The problem of intergranular corrosion is significant in welding of stainless steels, causing what is known as weld decay. This phenomenon significantly aggravates the strength of the weld.

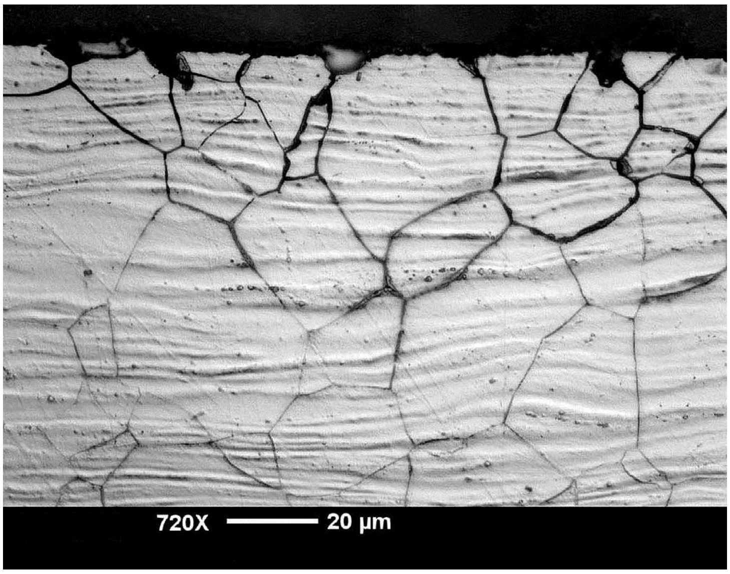


Figure 14: Intergranular corrosion on the surface of a metal.

- Stress corrosion cracking

Stress corrosion is the phenomenon that occurs by combining tensile stress in a corrosive environment. This particular type of failure poses significant problems to structures, for the following reasons:

a) It can manifest itself in metals otherwise inert to corrosion.
b) During SCC, cracks are created on the metal. They eventually propagate and lead to brittle fracture, event for an otherwise ductile material. This eliminates any room for warning, since no visible deformation is observed before failure.
c) It can cause failure to stress levels significantly lower than the tensile strength of the material. This means that failure to consider the SCC factor at the design stage could lead to structural failure.
d) The imposed stress can also stem from residual tensions or temperature changes, making prevention of SCC harder.

Alloys are more prone to SCC than pure metals. Prevention of SCC can be achieved by:

a) Reduction of the tensile stresses through reduction of external loads, or annealing to relieve internal stresses created during the manufacturing process.

b) Substitution of the material with another, less prone to SCC.

c) Isolation of the material from the corrosive chemical substances.

Multiple mechanisms can cause SCC. Till to date, three basic mechanism for SCC have been identified (Cottis, 2000). These are:

- Film rupture model

Ductile materials are usually coated by a protective brittle film created by corrosion. Application of tensile stresses can rupture that film and reach into the ductile core. The area is exposed to the corrosive environment. As a result, a new protective film is created in the crack tip. Repeated applications of the load can lead to multiple ruptures on the film, reducing the material's strength and causing fracture.

- Pre-existing active path model

In this process, corrosion happens faster along an area of high susceptibility, while the majority of the material remains passive. The most common path are grain boundaries. This is so, because the concentration of impurities during the solidification process makes this area harder to passivate.

- Embrittlement model

Hydrogen is a small atom, which makes it easy to fit between the metal atoms that form the metallic crystal. As a result, it diffuses at higher rates than larger atoms. It tends to be attracted to regions of high tensile stress where the metal structure is dilated. The dissolved hydrogen then assists in the fracture of the metal, possibly by introducing plastic deformation to the crystal. That makes the material brittle.

Most of the corrosion met at ships is worsen by the simultaneous application of stress. For an accident to be declared SCC-related, however, the role of corrosion must be significant.

For the scope of this study, accidents due to SCC will be perceived as corrosion-related.

4.1.2 Methods of prevention

The dangers imposed by corrosion are evident and the economic cost for repairs is high. Corrosion damages can often render a ship unseaworthy and the repairs inexpedient. As a result, efforts are concentrated in the development of prevention measures. The most notable actions to this direction are (Dražić, Stojan & Kulenović, 2011):

- Protection Coatings

Every part of a ship's surface -whether underwater or not- is covered in some kind of coating. Even before construction, a primer is applied to every plate that comes out of the workshop in order to provide protection from corrosion. After assembly, abrasives are used to prepare the metal surface for the next step. Finally, a layer of coating is applied by spray, paint brush or –more rare- paint roller. Some coatings may have anti-fouling capabilities in order to prevent the growth of marine organisms on the hull's surface.

- Cathodic protection by sacrificial anode

This method makes use of electrochemical principles to protect a metal against corrosion while "sacrificing" another metal. Cathodic protection is prevalent in modern ships. The principle is the following: Two metals in contact through water (electrolytic environment) develop potential difference. Electric current (electrons) flow from the cathode to the anode. This results in ions being released from the surface of the anode which then dissolve to the surrounding water, corroding the anode material. The most commonly used material is zinc, which is welded onto the hull. This type of protection is used in combination with coating. It provides an inexpensive way of shielding the ship from corrosion. However, it has a limited lifespan and must be replaced every 1 to 5 years, depending on ship size, coating quality and other factors.

- Cathodic protection by induced current

Similar to the sacrificial anode method, this technique uses an external source of current to accelerate the electrochemical reaction between the anode and the cathode. Although having higher installation cost, this method can provide a better customized protection solution by altering the current according to external parameters (ship size, sea water salinity, damaged surface extent, etc.)

- Corrosion resistant materials

The most commonly used material for shipbuilding is standard (grade A) steel and high strength steel. Those materials provide sufficient strength but lack resistance to corrosion. Even the areas out of the water are exposed to salted moisture that can progressively corrode the surface. A trend of using stainless steel in areas most prone to corrosion has emerged in the last years. Areas such as cargo space and piping can be constructed from stainless steel and can be specially welded in order to prevent corrosion. However superior it might be in dealing with corrosion, stainless steel usage in hull is impossible, due to the increased cost per ton. As a result, it's not used in extensive areas. In such cases, coating of standard steel is preferred.

4.2 Cracking

Fracture (or cracking) is the separation of a mass into two or more pieces, as a result of stress application. Different types of fracture exist, depending on the conditions that led to failure. For example:

- Simple fracture is a result of static stress application at low temperatures compared to the material's melting point.
- Fracture due to fatigue occurs when cyclic stress is applied to the material. This type of fracture can occur at lower stress values that the material's strength under static tensile stress.
- Creep is a time-dependent deformation that occurs in high temperatures.

Moreover, according to the experienced deformation fractures are also classified into:

- Ductile, when substantial plastic deformation happens before the fracture occurs.
- Brittle, when little deformation occurs before the fracture.

For example, metals under static tensile stress usually undergo ductile fracture, whereas glass and other ceramic materials fracture in a brittle manner (Callister & Rethwisch, 2010).

In most cases, ductile fracture is preferable in structures. This is so, because deformations before fracture act as warning signs that trigger intervention before failure occurs. Furthermore, ductile materials have generally higher fracture points than brittle ones, making them tougher in load bearing.

Ductile and brittle fracture are easily distinguishable by the morphology of the fracture surface as well as the mechanism of failure. Ductile materials under tension become thinner as the tension rises, a phenomenon called "necking". The more ductile the material, the greater the necking. Brittle materials, on the other hand, break without any substantial plastic deformation. As a result, no necking is present. The following illustration depicts the deformation for each material category.

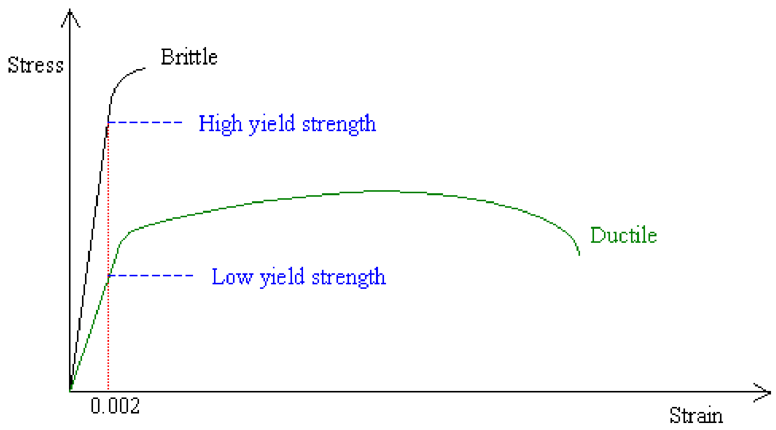


Figure 16: Stress-strain diagram for a brittle and a ductile material. Ductile materials can take on much larger deformation before fracture.

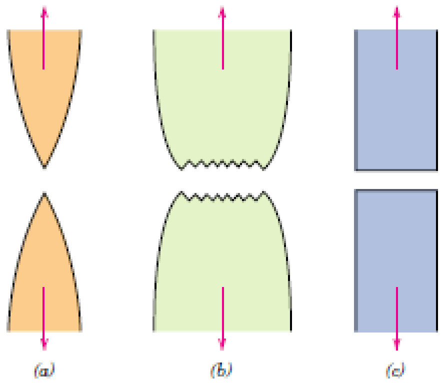


Figure 15: Fracture point for a perfectly ductile material (ideal-left), a completely brittle material (ideal-right) and a material of intermediate characteristics (middle).

4.2.1 Ductile fracture

From stress application to the final fracture, the metal undergoes a series of transformations: First, an initial neck is created. As the stress increases, small voids in the neck area start to appear. These voids are formed in more vulnerable areas of the metal, such as areas containing impurities and other defects. As the tension increases, these voids become larger and merge together to form larger spaces. The voids finally unite under one large cavity of elliptical shape, with its large axis perpendicular to the direction of the stress.

Increasing the stress leads to rapid crack propagation and ultimate cracking in a 45° angle relative to the stress axis. An illustration of the stages is shown below:

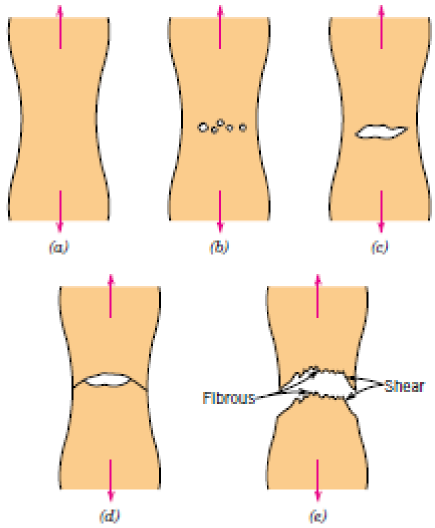


Figure 17: The internal mechanism of cracking at different stages.

4.2.2 Brittle fracture

In contrast with ductile fracture, brittle fracture does not create any significant deformation. The direction of the crack plane is perpendicular to the direction of the applied stress. This type of fracture is characterized by rapid crack propagation and low energy output.

The fracture surface for brittle materials is distinctive. Two main formations might occur (Pantelis & Chrysoulakis, 2008):

- Transgranular fracture

This type of fracture occurs when the line of crack propagation passes through the individual grains of the metallic structure and separates them. The crack passes through weaker crystallographic planes, called cleavage planes. This change in the orientation of the planes causes the fracture surface to be coarse.

- Intergranular fracture

In metals with significant presence of secondary phases or impurities concentrated in the grain boundaries it’s common for intergranular fracture to occur. Such fracture is caused by cracking along the grain boundaries, while individual grains are left intact. As a result, it is most commonly met in metals that have been weakened by mechanical stress or intergranular corrosion.

5. The Notion of Risk

Any attempt to define risk would be fruitless without first defining its key mathematical elements: probability and frequency.

5.1 Random experiment

A random experiment is an experiment whose results cannot be accurately predicted in advance, but can only be known after it has been executed. Different executions of a random experiment will render different results, under the same conditions. In order to handle such experiments, one must find a way to mathematically model the uncertainty accompanying them. The mathematical notion that makes this possible is called *probability* (Kokolakis & Spiliotis, 2002).

5.2 Probability

Before any attempt to define risk, it is necessary to address the meaning of probability, since "modern risk analysis has its twin roots in mathematical theories of probability" (Covello & Mumpower, 1985). Webster's defines probability as 'a measure of how likely it is that some event will occur' (Webster's dictionary, "probability"). This definition –however simplistic it may seem- is fully acceptable from a literature standpoint. It lacks, however, mathematical formulation, without which it is impossible to make any calculations.

The most widely accepted mathematical definition of probability comes from A.N. Kolmogorov in his 1933 monograph *Foundations of the Theory of Probability*. According to the axioms stated, probability is a function which assigns real numbers to sets of events. A function can be called a "probability function" if all of the following criteria are met (Kokolakis & Spiliotis, 2002):

- $P(\Omega) = 1$, where Ω symbolizes the sample space of the random experiment. A sample space is a set containing all the possible outcomes of the experiment. Every trial will result in an event included in the sample space, thus the probability for Ω to occur is 100% or 1. A coin toss throw will always result in either head or tales, which are all the possible outcomes for this experiment.

- $P(A) \geq 0$ for any event A. An event A is a set of possible outcomes for the experiment. Any subset of Ω is called an event. For instance, A={1, 3, 5} is the event of having odd result after a die throw. If any of 1, 3 or 5 is realized, the event A is realized.

- $P(A_1 \cup A_2 \cup \cdots) = P(A_1) + P(A_2) + P(A_3) \cdots$ if A_1, A_2, A_3, … have no elements in common.

The definition of probability has little to no use when it comes to assigning values to real life random experiments. For example, a "head and tales" coin experiment might have a 50-50 chance for heads and tales, but could also have 60-40, 70-30, 83-17, etc. without violating the previously mentioned rules. In order to assign specific probability values to events from observations, *frequencies* should be used.

5.3 Frequency

In statistics, relative frequency (or empirical/experimental probability) of an event is a measure of how many times a specific outcome has occurred over a total number of trials. It is calculated by dividing the number of outcomes an event has occurred (m) by the total number of trials (n) (Mood, Graybill & Boes, 1974).

$$f = \frac{m}{n}$$

According to statistics, if an experiment is repeated for a large number of times, the ratio m/n will have a very small difference from the corresponding theoretical probability value $P(A)$. In other words, the frequency converges to the value of the corresponding probability as the number of repetitions increases. As a result, empirical probability can be used as an estimation of the mathematical probability. In mathematical notation:

$$\lim_{n \to \infty} \frac{m}{n} = P(A)$$

The issue with this formula is that it requires an infinite number of experiments in order to assess the probability of a single event. As this is practically impossible, a compromise in accuracy must be done in order for the calculation to be feasible.

The graph below shows the converge of frequency of number 3 to appear on a fair dice, done for 5 series of random experiments.

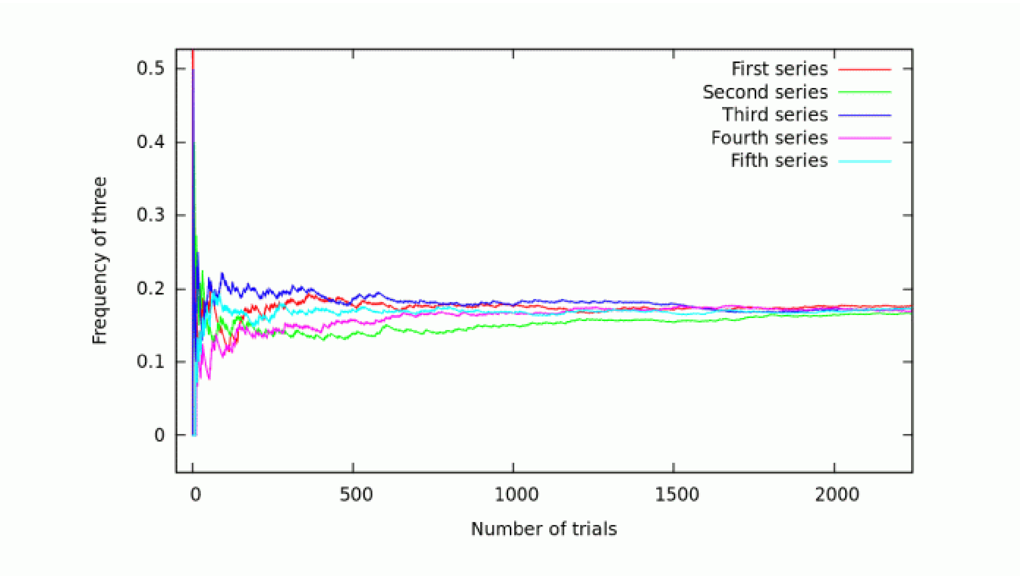


Figure 18: For a large number of repetitions, the frequency tends to converge to a single value. This value approximates the probability for the corresponding event.

All frequencies tend to converge around 16.67% which is an estimation of the probability of number 3 to appear, since:

$$P(A) = \frac{N(A)}{N(\Omega)} = \frac{1}{6} \approx 16.67\%$$

5.4 Risk

A key concept for every safety analysis, risk can be defined in many ways:

- From a financial perspective:
  "Risk involves the chance an investment's actual return will differ from the expected return. Risk includes the possibility of losing some or all of the original investment."[1]
- From a food industry perspective:
  "The possibility that due to a certain hazard in food there will be an negative effect to a certain magnitude."[2]
- You might hear a physicist say:
  "Professional athletes risk injury every time they train, practice, and compete."

No matter the context, all the above definitions appear to have a common base:

Risk is a random event that –if it occurs- can lead to negative impact (Vose, 2008).

According to this definition, three elements are of importance:

- Random event

  Risk is associated with an event.

- "If it occurs"

  In other words, the likelihood that something will occur. This can be quantified by the use of probabilities.

- Negative impact

  The magnitude of this impact (severity) is a key element to risk. As a result, a method to quantify the impact must be established.

According to Risk Analysis, risk is defined by the following formula:

$$Risk = Probability \times Severity$$

[1] http://www.investopedia.com/terms/r/risk.asp
[2] http://www.businessdictionary.com/definition/risk.html

6. Formal Safety Assessment (FSA)

FSA is a systematic methodology used to help decision-makers on the IMO to decide on new safety regulations. It is a holistic approach on safety issues that can be extended to any industry. It consists of 5 steps (Imo.org, 2016):

1. Hazard Identification (HAZID)

A list of all relevant accident scenarios is recorded, along with potential causes and possible outcomes. For this purpose, a team of experts from various positions in the industry (Academics, surveyors, naval engineers, etc.) is assembled to contribute with their experience.

2. Risk Assessment

Evaluation of risk factors is performed. In specific, both severity and frequency of an event are calculated using statistical analysis and empirical models.

3. Risk Control Options (RCOs)

Proposition of regulatory measures (both technical and in the form of legislation) that aim to the reduction of the risks identified.

4. Cost-Benefit Assessment

Determination of the cost effectiveness of each risk control option.

5. Recommendations for decision-making

The final step includes recommendations for the decision-makers according to the findings of step 4.

Schematically, the process is depicted in the following diagram:

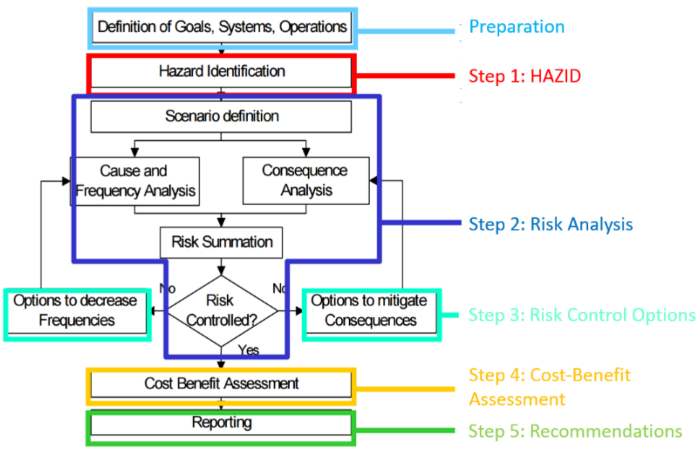


Figure 19: Diagram of the FSA process.

6.1 Step 1: Hazard Identification

The purpose of this step is to generate a list of possible accident scenarios for later processing. Expert judgement is necessary to ensure that all chosen scenarios are plausible, while excluding those that are of least concern. For the elaboration of this task sufficient data must be available. Casualty databases serve as a basis for research, though more detailed reporting may be needed for further study. This step is of utmost importance, since it dictates which hazards will be considered for later processing. Failure to include a significant accident scenario in this step will lead to a deficient study (Kontovas & Psaraftis, 2009).

Many methods are used in the HAZID process. Some of the most common are (Ericson, 2005):

- What-If Analysis/SWIFT

What-if analysis is an inductive hazard analysis method that involves simulating the behavior of a complex system under some set hypotheses (scenarios). Specifically, the reaction of the system is assessed in reference to changes in the input parameters. As a tool, it can be used in a variety of fields, such as economics, business, psychology, engineering, etc.

Compared to other methods, such as Hazard and Operability Study (HAZOP) this process does not require extensive planning and complex quantitative methods. As a result, less experience is needed in order to use it. On the other hand, thorough knowledge of the system in hand is an absolute necessity.

The table below is an example of What-if/SWIFT analysis performed on a ship's ballast system.

Ref	What-If?	Causes	Consequences	Safeguards	Recommendations
1	Inadequate ballast system design	Lack of experience at shipyard; lack of regulation; poor design process or quality checking; financial constraints	Pump system capacity too low. Inability to ballast efficiently.	Class/IMO rules Plan approval process.	
2	Failure of ballast system	Failure of pumps, valves, pipes etc.; suction blockage	Inability or reduced ability to ballast. Unable to correct heel.	Design Redundancy Maintenance	Ballast system should be surveyed in operation and performance tested
3	Inadequate planning of ballast operation	Inadequate training; time pressure; inaccurate weather forecast	Potential incorrect ballast operation.	Training Procedures	Training should emphasize hazards associated with ballasting.
4	Maloperation of ballast system	Failure to follow ballast plan; unclear ballast procedures; maloperation of valve; wrong sequence of valve operation; inadequate training; time pressure	Unfavourable heel/trim or draught	Training Procedures Planning Monitoring	Ballast procedures should include requirements for monitoring

[HSE, 2001]

Figure 20: A "what-if" analysis worksheet. Causes, consequences, as well as recommendations are proposed for every conceived hazard.

- Hazard and Operability Study (HAZOP)

Hazard and Operability Study (HAZOP) is a systematic technique for examining complex systems in order to detect hazards to humans or equipment that would otherwise go undetected. It is performed by assuming divergence from the normal operational state of the system and calculating its consequences. In the case of technological entities, the system is broken down to key sections and any component is assessed against possible deviations from its normal state by using key-words for guidance. Some basic key-words are: No, more, less, reverse, other than, as well as, etc. Each question should be answered in terms of causes, consequences, existing safety measures, as well as possible actions to mitigate any adverse effect. .

HAZOP presents many similarities to what-if/SWIFT analysis. Like what-if analysis, HAZOP requires a team of experts. However, it is more data-intensive and time-consuming than what-if analysis.

- Failure Mode and Effects Analysis (FMEA)

FMEA is a systematic process used to identify various failure modes of equipment and to assess their consequences. This method produces a qualitative list of equipment, failure modes and consequences for these failures. It is not ideal, however, for identification of different combinations of system failures. As it holds true for any method used for hazard identification, excellent knowledge of the system at hand is a perquisite for a reliable analysis.

- Task Analysis (TA)

The previous methods focus almost exclusively on equipment. When it is present, human element contribution is incorporated into the numbers of equipment failure without a separate reference. The method most commonly used when assessing the contribution of the human factor is TA.

TA analyzes how to task is performed, by making a hierarchical list of the sub-tasks required for its completion. Essentialy, it involves breaking a large task into smaller ones that are easier to carry out. The level of detail in breaking down a task into simpler ones depends on whether the analyst thinks that a significant failure can occur with the current level of analysis.

Data for TA is collected through interviews and observation of operating procedures. A diagram is then created using a hierarchic structure, starting from each individual sub-task and ending up to the main event. Below follows an example of TA regarding the process of boiling water into a kettle.

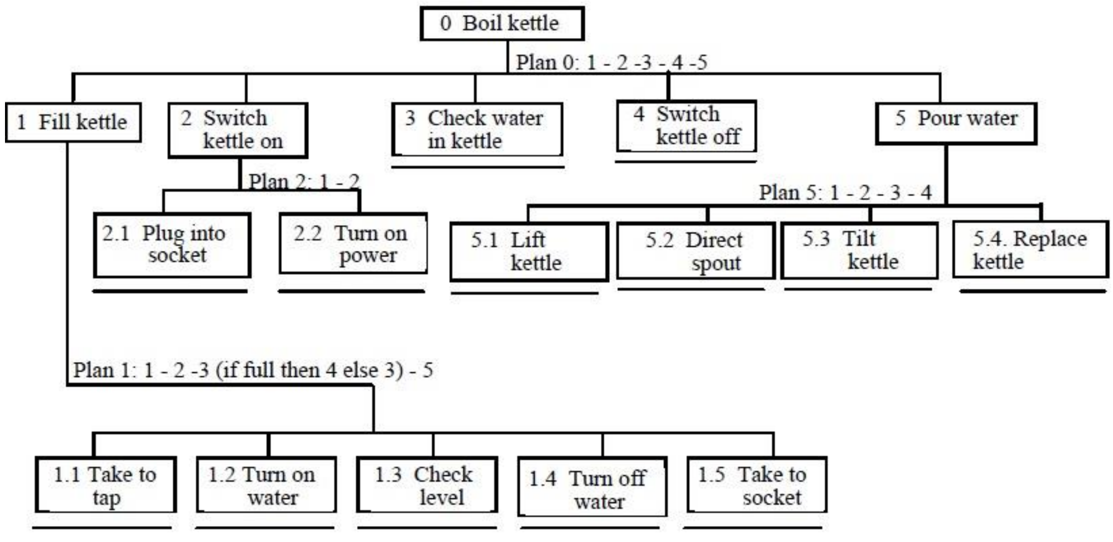


Figure 21: Example of a Task Analysis diagram for the process of boiling water into a kettle. TA diagrams such as this can simplify complex problems by breaking them into smaller –more manageable- ones.

The above list of methods is not exhaustive. It contains the most commonly-used methods used for HAZID. Not all methods are equivalent, however, and differences do exist between each approach. Choosing between them relies in many criteria, such as:

- Available time

Regardless of the method used, HAZID is generally a lengthy and labor-intensive process. The composition of the expert team, as well as the time spent are carefully monitored and regulated. For instance, HAZID meetings for IMO should last no more than 5 to 6 hours per day in order to avoid poor judgement due to fatigue. Overall, such a meeting should not last more than 3 days.

- Available budget

Budget restrains might favor one method over another. HAZID is a costly venture, because it requires a large team of highly qualified professionals, as well as the collection and processing of data. Depending on the budget allocation of each respective organization and the overall importance placed on the study, one could choose a less source-demanding method over a costlier one.

- Degree of detail required

HAZID performed for a nuclear power plant is expected to be more thorough than the one performed for an automobile parts manufacturer. The stakes in the first case are much larger. There is no 'one size fits all' philosophy, and different methods appeal to different needs.

Once all plausible scenarios are listed by category (ex. spatial or structural similarity), the less risky ones are excluded from the study. To perform this task, each accident is assigned with 2 indexes (Kontovas, 2005).

- Severity Index (SI)

It takes integer values from 1 to 4 and quantifies the severity *(how bad?)* the outcome is in relation to specific consequences, such as loss of human life, environmental impact and damage to property.

- Frequency Index (FI)

It is assigned with integer values from 1 to 7 and quantifies the frequency (likelihood) of the respective scenario to happen.

After both SI and FI are evaluated for each scenario, the Risk Index (RI) is calculated as the sum of the 2 indexes:

$$RI=SI+FI$$

The risk index takes integer values from 2 (not risky) to 11 (extremely risky).

At the end, a threshold risk value for accepting a scenario is established and scenarios below that threshold are excluded from the study as non-significant.

Table 1: Typical risk matrix used in Hazard Identification step (HAZID). Orange accident scenarios are excluded from the study.

Risk Index (RI)					
		SEVERITY (SI)			
		1	2	3	4
FI	FREQUENCY	Minor	Significant	Severe	Catastrophic
7	Frequent	**8**	**9**	**10**	**11**
6		**7**	**8**	**9**	**10**
5	Reasonably probable	**6**	**7**	**8**	**9**
4		**5**	**6**	**7**	**8**
3	Remote	**4**	**5**	**6**	**7**
2		**3**	**4**	**5**	**6**
1	Extremely remote	**2**	**3**	**4**	**5**

After significant scenarios are established, Event Tree Analysis is used to display the progression of the accident in a diagrammatic approach.

6.2 Step 2: Risk Assessment

Any attempt to describe risk analysis would be fruitless without prior knowledge of Probabilistic Risk Assessment (PRA). This is because risk assessment heavily relies in the use of PRA.

6.2.1 Probabilistic Risk Assessment (PRA)

Realistic accident scenarios, as well as accurate probability and severity values should be properly assessed before risk analysis is performed. The methodology to assess risk in known as *Probabilistic Risk Assessment* (PRA).

By definition, PRA is "a systematic and comprehensive methodology to evaluate risks associated with every life-cycle aspect of a complex engineered technological entity" (Stamatelatos, 2000). It's a robust methodology capable of dealing with risk-related issues in many industries, such as nuclear power, aerospace, chemical, automotive, as well as the maritime industry. PRA provides answers to 3 basic questions:

1. What can go wrong?

A list of all possible accident scenarios that can lead to unwanted consequences is created.

2. How severe are the potential accidents?

The severity of each accident scenario is quantified and assessed.

3. How likely is that these events will occur?

The probability for each scenario is calculated.

The method can be used at the design stage of a complex system in order to shed light to design flaws and to propose cost-effective solutions to mitigate the risk associated with them. It can also be used as a post-construction tool to assess risk in an existing system/structure and to detect reduced safety aspects (Stamatelatos, 2000). Within the maritime industry, PRA is put into action through FSA.

PRA employs a set of analytical tools in order to generate results. The most important ones are described in the next page.

6.2.1.1 Event Tree Analysis (ETA)

ETA is a diagrammatic representation that identifies and quantifies the possible outcomes that may rise from an initiating event. The diagram is in the form of a tree, with each branch representing a different direction for an accident to propagate and each node represents a junction with possible routes of progression. By assigning probability values to each individual event, the total probability for each accident scenario can be calculated as the product of each individual probability on the path (Ericson, 2005).

Creation of an Event Tree must comply with the following rules:

- Different paths should be mutually exclusive. If a specific path is realized, no other path should be possible.
- All possible accident scenarios should be covered. That means that each junction should add up to 100%.

Formation of an ET is a multi-step process. First, the system must be defined in order to find its boundaries and subsystems. Secondly, hazard identification should be performed in order to find all possible hazards and accident scenarios. This is where expert judgment becomes necessary. Thirdly, initiating events are identified. Such events act as starting points for accident propagation. Subsequently, intermediate (pivotal) events are listed and the Event Tree is constructed. Finally, event probabilities are assigned to each branch and risk is evaluated for each accident scenario.

The process of designing an ET is summarized in the diagram below.

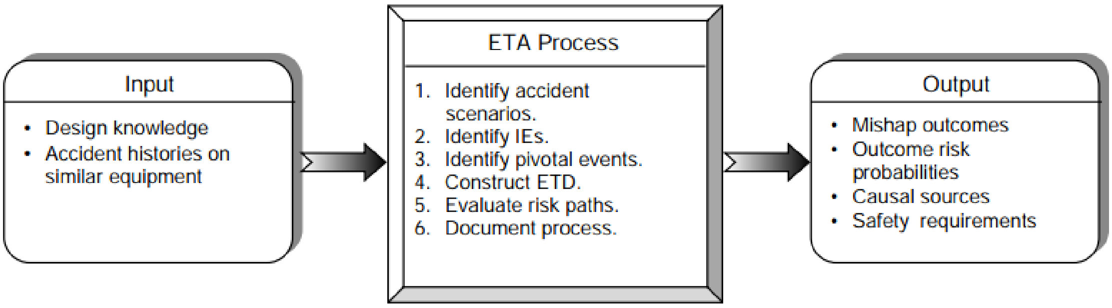


Figure 22: A diagram showing the process for performing ETA.

The example below illustrates how ETA works.

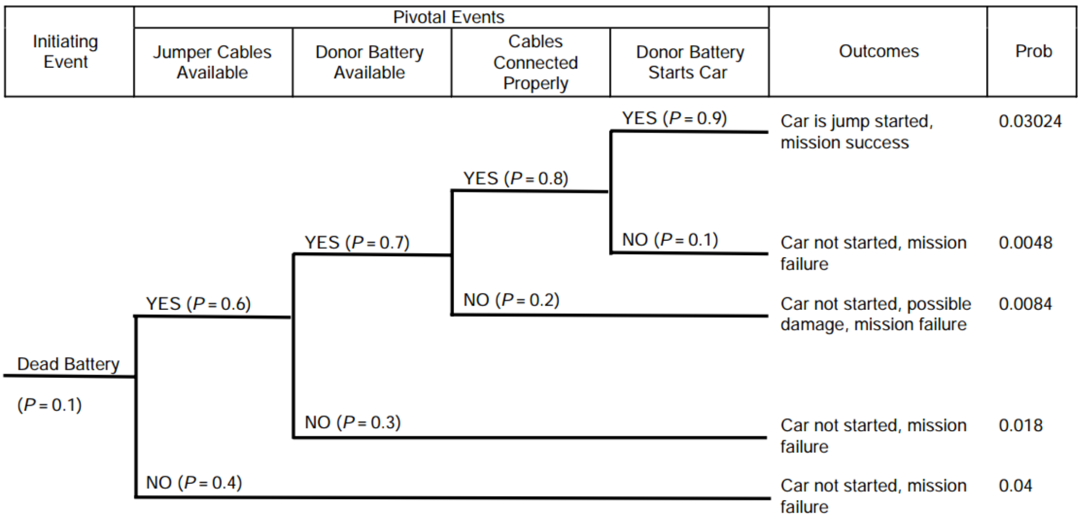


Figure 23: An example of an Event Tree, along with probability calculations.

This example refers to a car having a dead battery (initial event). Many actions can be taken to jump start the engine, but for the sake of simplicity it's been assumed that the only available solution is to give life to the existing battery by recharging it (and not, for example, buy a new battery). Pivotal events are displayed in a logical order. For instance, "Donor Battery Available" should precede "Cables Connected Properly". For each event, probabilities are assigned. The values should add to 100% for each event, since branches should be individually exclusive. For instance, "Jumper Cables Available" can either be true (Yes) or false (No). If one state happens the other cannot be realized at the same time. In order to evaluate each path (accident scenario), multiplications between corresponding values are performed.

For example, the path: Dead Battery (0.1) →Jumper Cables Available (0.6)→No Donor Battery Available (0.3) has a total probability value of 0.018, or 1.8% (0.1 x 0.6 x 0.3 = 0.018).

Obviously, the sum of all possible outcome probabilities should add to 0.1 (the probability of the initial event). Indeed, 0.03024 + 0.0048 + 0.0084 + 0.018 + 0.04 = 0.101 (minor divergence occurs due to rounding errors).

In case of this ET, the initial event does not have a 100% chance of actualization. That means that the tree is part of a larger ET which is not shown here.

6.2.1.2 Fault Tree Analysis (FTA)

First used in 1962 by Bell Telephone Laboratories as a system reliability evaluation tool, FTA is the graphic representation of the link between basic events that gradually lead to a major unwanted event (top event). Unlike ETA, which is an inductive process, FTA is a deductive technique that starts from an undesired event (top event) and deduces its possible causes in a reverse order. That makes FTA a proactive tool in the direction of preventing the top event, while ETA is a passive method that presents the process between the top event and the final consequences (Ericson, 2005).

Fault Tree Analysis makes use of Boolean algebra and probability theory. An unwanted event (called the Top Event) is logically broken down to more basic components, represented by an event box. Event boxes are joined together as a tree by the use of logic gates. Logic gates represent the interaction between the basic events that can lead to the realization of the top event. The most common gates used are: “AND” and “OR” gates. An “AND” gate signifies that in order for the event to occur, all the events under the gate must be realized. An “OR” gate states that only one of the events under the gate is necessary to be realized for the event to happen. Of course, more than one events can happen. From a mathematical standpoint, “AND” gates are treated as the section between two or more probabilities (A and B and C translates into $P(A \cap B \cap C)$). “OR” gates are treated as unions (A or B or C translates into $P(A \cup B \cup C)$).

A table of the most commonly used logic gates is depicted in the following page. A and B are inputs, C is the output. Calculation of each gate is done according to probability theory.

Table 2: Some common logic gates used in Fault Tree Analysis, along with their function and mathematical formula for calculation.

Name	Function	Probability formula
OR	The output occurs if at least one of the inputs occur	$P(C) = P(A \cup B)$
AND	The output occurs if all the inputs occur	$P(C) = P(A \cap B)$
Exclusive OR	The output occurs if exactly one input occurs	$P(C) = P[(A \cap B') \cup (A' \cap B)]$

The following example illustrates how a fault tree is calculated:

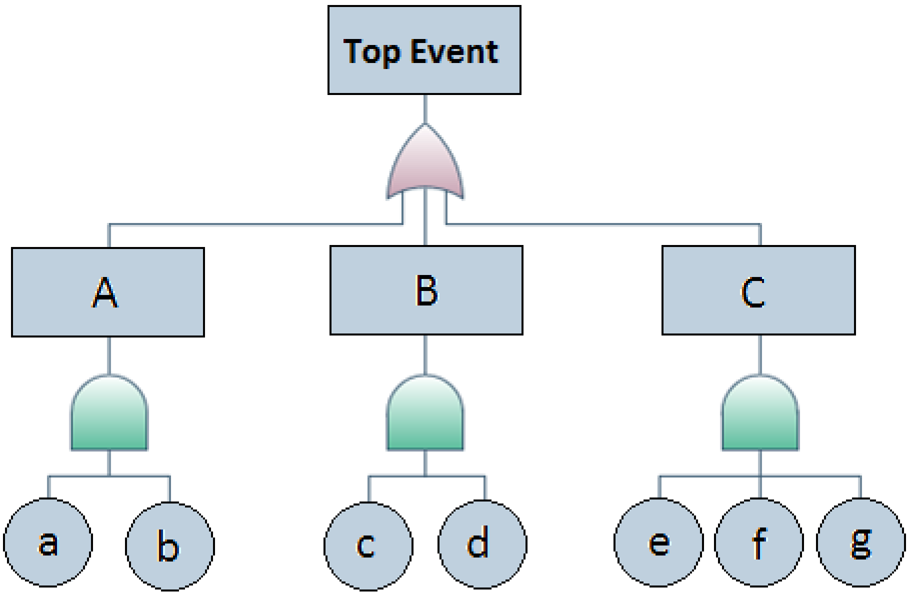


Figure 24: A simple FTA diagram. Logic gates, event boxes and the top event are depicted.

$$P(Top\ Event) = P(A \cup B \cup C)\ (1)$$

Since A, B, C must be mutually exclusive,

$$P(A \cup B \cup C) = P(A) + P(B) + P(C)\ (2)$$

Each one of the A, B, C is constructed by the section (AND gate) of more basic (lower level) events.

$$P(A) = P(a \cap b)\ (3)$$

$$P(B) = P(c \cap d)\ (4)$$

$$P(C) = P(e \cap f \cap g)\ (5)$$

By substituting (3), (4) and (5) to (2) one gets:

$$P(A \cup B \cup C) = P(a \cap b) + P(c \cap d) + P(e \cap f \cap g)$$

Since a and b, c and d, e, f and g are considered independent of each other,

$$P(a \cap b) = P(a) \cdot P(b)$$

$$P(c \cap d) = P(c) \cdot P(d)$$

$$P(e \cap f \cap g) = P(e) \cdot P(f) \cdot P(g)$$

Therefore,

$$P(Top\ Event) = P(a) \cdot P(b) + P(c) \cdot P(d) + P(e) \cdot P(f) \cdot P(g)$$

The creation of a fault tree model is comprised of five distinct steps:

1. Definition of the major undesired event

The major undesired event (top event) is the starting point of FTA. All other events will logically stem from it. Thorough knowledge of the system at hand is essential.

2. Event break down

The top event must be logically decomposed to simpler events and the interaction between those causes must be established. The analyst should be very careful not to omit any possible cause that affects the top event, since doing so will lead to an unreliable model. Excellent understanding of the system is necessary.

3. Construction of the tree

The fault tree is constructed according to the relations established in the previous step.

4. Evaluation

The fault tree is tested for mistakes and is corrected accordingly.

5. Control of the hazards

Measures for lowering the top event probability are taken. This can be performed by either reducing high probability events or by redesigning the system (altering the connection between events or introducing additional events to lower the overall probability).

As it holds true for any analytical tool, FTA presents some advantages and disadvantages.

Advantages:

- Easy to understand, due to its graphical representation.
- It can be used in the design process, as well as a post-evaluation tool.
- Easy to implement, since it makes use of elementary probability theory and Boolean algebra.
- Provides a qualitative look into the system and its parameters of failure.
- Provides quantitative data overall, as well as for specific branches.

However, FTA also has limitations, such as:

- Difficulty to conceive all possible causes and interactions leading to the top event. This holds especially true for more complex systems.
- Correlation between events (AND/OR association) is not always clear to establish.
- A level of subjectivity is present. Various analysts may use different approaches and level of detail for the same system.
- Quality numerical data for each event cannot always be found. To mitigate this problem, assumptions have to be made. Depending on the accuracy of the data inserted, the result might be more or less accurate.

6.2.1.3 Bow tie diagrams

Bow tie diagrams are widely used in the field of risk management in various industries. They provide a holistic way of communicating risk management among interested parties. In specific, a bow tie diagram provides a qualitative view on the mechanism through which causes lead to a hazard, which in turn can lead to unwanted consequences. The term 'holistic' applies here, due to the fact that it displays the complete propagation sequence of an accident from start (causes) to finish (consequences), unlike other methods.

It is constructed around a hazard, which is presented in the center of the diagram. On the left side lie the causes (threats) and the interactions between them. This part is presented by the use of FTA. At this stage, accident prevention is proactive, meaning actions can be taken to prevent the hazard from appearing.

On the right side of the top event, a consequence tree is constructed using ETA to showcase how the hazard (top event) escalates to its final consequences. Most often, the final consequences involve loss of life, environmental pollution and damage to property. This part of the diagram is said to be reactive, meaning that the measures taken at this stage only help to mitigate the consequences and not treat the source of the problem. The top event itself presents a point in time where control over the incident is lost (Saud, Israni & Goddard, 2013).

An example of a proactive measure to prevent fire in a house would be the use of fireproof construction materials and taking cautionary measures when using heat sources, such as the iron or the stove. A reactive measure (after the fire has presented) might be the use of fire extinguishers or a fire alarm.

The typical form of a bow tie diagram is pictured below.

Figure 25: A typical Bow-Tie diagram.

The use of bow tie diagrams has the following advantages:

- It provides a holistic understanding of risk, from start to finish.
- It is easy to understand by any interested party, without requiring advanced knowledge in the field of risk analysis and risk management.

The main disadvantages of these diagrams are:

- They cannot be implemented in early stages of the risk analysis process, since knowledge of the “whole picture” is necessary.
- They lack quantitative data, which makes them unsuitable for risk assessment.

6.2.2 Risk Assessment

The scope of this step is to assign risk values to the accident scenarios identified in step 1 (HAZID). The consequences are of 3 types:

- Loss of human life
- Environmental pollution
- Property damage

Loss of human life (abbreviated LOL) is defined as the number of people who lost their lives as a direct result of the accident. Injuries are considered as fractions of the unit: One severe injury equals to 0.1 fatalities whereas one minor injury equals to 0.01 fatalities.

Environmental pollution (“Environmental Impact” or EI) is expressed in tons of oil spilled in the sea as a result of the accident. No other substances are considered when evaluating this metric. It’s worth noting that a sunken ship is considered to have an EI equal to the tones of oil it carried, regardless of whether the oil was spilled or not. This is so, because –sooner or later- corrosion and harsh conditions in the bottom of the sea will breach the hull and subsequently the oil will be released.

Finally, damage to property (or “Damage To Ship”-DTS) is calculated in monetary units (US dollars) needed for the replacement of the damaged part. In the case of total loss, the newbuilding price is taken as DTS, expressed in current market price, after adjusting for inflation over the years. When calculating the price of replacement, the following factors are taken into consideration:

- Cost of repairs
- Loss of income due to idleness
- Cost of human life (in the event of fatality/injury)
- Value of cargo lost or damaged
- Value of the ship (in the case of total loss)

Quantification of the consequences can be performed in a variety of ways, such as statistical analysis, specialized software, etc. As already stated, risk is the product of probability times severity (consequences) of an unwanted event. After assessment of the consequences in numerical values, the probability of each accident scenario is evaluated by means of statistical analysis. Reliable data is extremely important at this stage in order to provide realistic risk values.

For the completion of this step, a range of analytical tools is employed. ETA and FTA are the most prevalent.

The overall risk model is depicted in the form of a Risk Contribution Tree. This depiction consists of a Fault Tree and an Event Tree in combination. In detail, a fault tree is used to showcase the connection between different failures that can lead to an accident initiating event (also called the top event). From this point, ETA is used to display the sequence of events between the top event and the final consequences.

In the end, the accuracy of the results depends on:

a) The choice of work method, and

b) The quality of the data used.

Between these two factors, the second one (quality of data used) is more significant. More often than not, databases lack necessary information in a non-systemic manner. For instance, a specific accident might be properly recorded, while a more severe casualty can be left underreported. This is caused by the following reasons (Devanney, 2008):

- Casualty data is largely confidential. The legal framework of classification societies and some flag states is structured in such a way that prevents any interested third parties to obtain information without prior consent of the client.
- Casualty nomenclature is often broadly defined, leaving room for misinterpretations and subjectivity. For instance, a hull breach might be caused by corrosion or by crack. In the case of a mildly corroded surface one surveyor could rule that the cause of the accident was corrosion-related. Another surveyor could decide that the breach was mainly caused by severe stress and corrosion only played a secondary role. Furthermore, hardly any accident is caused solely by one cause. Multiple causation can create issues with reporting as well.
- Accident surveyors are prone to corruption. It's a usual practice to underreport casualties in order to avoid detentions. While major accidents are hard to conceal, minor incidents can be left completely unreported. Especially in the

case of occupational accidents reporting is scarce: Even fatalities are sometimes omitted from the reports.

In order to offset the effects of reporting deficiencies, expert judgment is employed. Many professionals from different aspects of the industry come together to form a working group. Lack of necessary information is substituted with experience and knowledge.

6.3 Steps 3 & 4: Risk Control Options & Cost-Benefit Assessment

These steps address the issue of what aspects can be improved in order to reduce risk of accidents effectively and how each proposition ranks in terms of cost vs. benefit. A series of steps is followed for this purpose.

First, areas of interest are identified, using data from the previous step (Step 2: Risk Analysis). The areas are screen according to the following factors:

- High overall risk value
- High probability value

Irrespective of overall risk value, high likelihood accidents are also addressed

- High severity value

Again, irrespective of total risk value, severe accidents are also included

- Low confidence accidents

In some cases there is high uncertainty surrounding certain accident scenarios. The value presented can significantly abstain from reality. In order to be on the safe side, uncertain scenarios are taken under consideration.

After specific scenarios are screened out, a brainstorming session takes place. During this process, experts come up with practical measures to minimize risk for the accidents under investigation. For example, "2nd RADAR for ships within 500-3,000 GT" is a potential measure to prevent collision and grounding accidents on such ships. At this stage, the options must be specific.

The next step is to assess the risk reduction capacity of each RCO proposed. This is done by reprocessing every relevant casualty and deciding whether a particular RCO would prevent the accident. The risk models are updated with new values obtained and the risk reduction is calculated as the difference between the initial value and the new one.

Furthermore, the monetary cost of each RCO is estimated (both installation and maintenance costs). It's not uncommon for prices of equipment to vary greatly in price, for instance due to country of origin, supplier, etc. To resolve this issue, an average price is taken.

For the Cost-Benefit Assessment (CBA) to take place, cost and benefit must be expressed in the same measurement units. Cost is assessed in monetary units (United States dollars), whereas consequences are calculated in different units. For instance, fatalities are measured in lives lost and environmental impact in tons of oil spilled. These units have to be converted in monetary values in order to be comparable to the cost. This is done by introducing metrics like NCAF (Net Cost of Averting a Fatality). After conversion, CBA is performed.

However, every input in the CBA is accompanied by a certain level of uncertainty. For certain cases, slight hikes in cost values can blot out any benefit. It is important that the CBA for each RCO is resilient to potential changes in cost. For this reason, sensitivity analysis is performed to each RCO. Elastic RCOs that can withstand relative changes in cost are deemed appropriate for implementation.

Finally, any additional information related to RCOs is stated and the process is completed (Kontovas, 2005).

6.4 Step 5: Recommendations for decision-making

In this final step, where recommendations and expert judgement are properly reported to regulatory authorities, along with suggestions for their implementation.

The proposals should be written in a manner that can be easily comprehended by all interested parties, no matter how experienced they are in the field of risk analysis. Furthermore, the recommendations should be presented in a traceable and auditable way. The reasoning behind any decision should be properly justified and backed by evidence, such as the results of risk analysis and cost-benefit assessment. The limitations of the proposed measures should also be stated. Finally, the composition of the team of experts that implemented the FSA should be noted.

The above measures aim to add transparency to the method, as well as to provide an effective communication channel between technical and regulatory personnel.

The proposed RCO's should be cost effective and reduce risk to a desired level. The notion of *desired level* is defined by taking into account both individual and societal risk. The values used by IMO are the following:

- Maximum tolerable risk for crew members: 10^{-3} fatalities/ship-year
- Maximum tolerable risk for passengers: 10^{-4} fatalities/ship-year
- Maximum tolerable risk for public ashore: 10^{-4} fatalities/ship-year
- Negligible risk: 10^{-6} fatalities/ship-year

According to these values, the risk of an accident might fall into one of the following three categories:

- Acceptable risk region, where no action needed
- Unacceptable risk region, where the risk should be reduced at any cost
- ALARP region. The risk that falls into this region should be reduced up to the point where its reduction is no longer economically feasible.

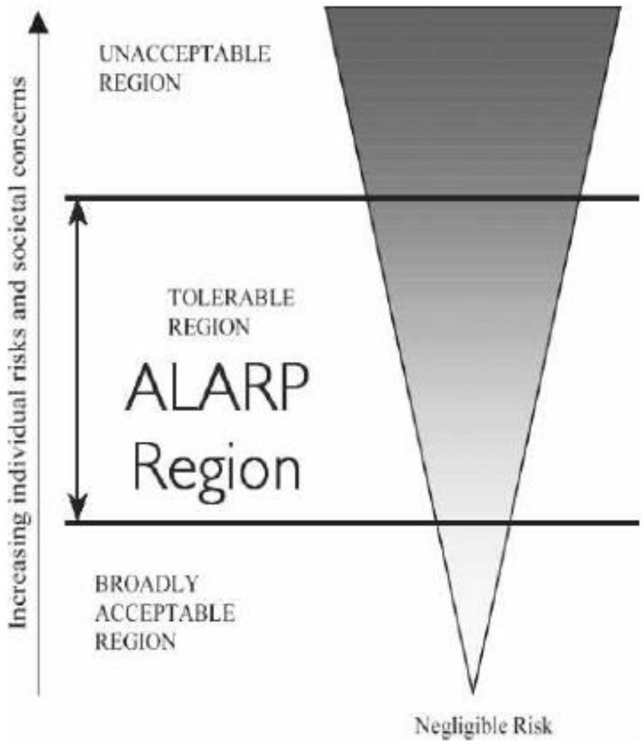


Figure 26: Risk regions. ALARP region in shown in the middle.

7. Research Method

7.1 Sea-web™ database

A database is a set of data organized in a manner that makes it easy to access, process and manage. The data is stored in the form of Tables consisting of records (rows) and fields (columns). Data input is achieved through a DataBase Management System (DBMS) through the usage of forms. Entry forms are visual interfaces that aid to process of data input by making it more user-friendly. Instead of having to insert data directly to the table, a form acts as an intermediate step between the user and the machine.

Another important component of DBMS are queries. Queries are questions that enable the user to retrieve data according to the specified criteria. Without queries, databases would be useless.

Finally, reports are used to display data in a way that it is both appealing and useful to the end user.

Sea-web™ is an online maritime database developed by IHS (now IHS Markit after merging with Markit Ltd. In July 2016). It provides intelligence on many aspects of the maritime industry, comprising one of the largest maritime databases in existence. Some of its features are (Anon, 2017):

- Over 200,000 detailed ship records of 100 GT and above.
- Up to 600 fields for each record
- More than 240,000 company records including ship owners, shipyards, operators, etc.
- Over 116,000 vessel photos
- Detailed vessel monitoring

7.1.1 StatCode5

Sea-web™ database classifies ships according to *StatCode5*, a widely accepted coding system for the classification of ship types. According to this approach, a code is assigned to each ship type. The code is constructed from left to right in sections, with each section representing a specific characteristic of the vessel (Chrysavgis, 2011).

The first character denotes the category of the structure, as follows:

A: Cargo Carrying Ship
B: Work Vessel
W: Non Seagoing Merchant Ships
X: Non Merchant

Y: Non Propelled
Z: Non Ship Structures

The second code element denotes the ship type:

A1: Tankers
A2: Bulk Carriers
A3: Dry Cargo/Passenger
B1: Fishing
B2: Offshore
B3: Miscellaneous

The third segment of the code depends on the type of cargo carried by the vessel:

A11:Liquified Gas
A12:Chemical
A13:Oil
A14:Other Liquids
A21:Bulk Dry
A22:Bulk Dry/Oil
A23:Self Discharging Bulk Dry
A24:Other Bulk Dry
A31:General Cargo
A32:Passenger/General Cargo
A33:Container
A34:Refrigerated Cargo
A35:Ro-Ro Cargo
A36:Passenger/ Ro-Ro Cargo
A37:Passenger
A38:Other Dry Cargo
B11:Fish Catching
B12:Other Fishing
B21:Offshore Supply
B22:Other Offshore
B31:Research
B32:Towing/Pushing
B33:Dredging
B34:Other Activities

The fourth segment further specifies the type of cargo being carried. For the sake of economy, only some of the categories are shown.

A11A:LNG Tanker
A11B:LPG Tanker

A13A:Crude Oil Tanker
A21A:Bulk Carrier
A21B:Ore Carrier
A31A:General Cargo
…

Finally, the addition of number two (2) denotes whether the vessel has a double hull. Following this number are two letters further specifying the characteristics of the ship, such as crane facilities, hatch types, etc.

For the purpose of this study, the prefix assigned to General Cargo ships is A31A. It is followed by other sequences accordingly. The list below summarizes all General Cargo vessel categories according to the StatCode5 system.

- A31A2GA (General Cargo ship with Ro-Ro facility)

A General Cargo ship with the additional capability to be loaded and unloaded by ro-ro access to a limited portion of the cargo space.

- A31A2GO (open hatch cargo ship)

A large single deck cargo vessel with full width hatches and boxed holds for the carriage of unitized dry cargo such as forest products and containers. Many are fitted with a gantry crane.

- A31A2GS (General Cargo/tanker (container/oil/bulk-COB ship))

A General Cargo ship with reversible hatch covers; one side is flush and the other is fitted with baffles for use with liquid cargoes. Containers can be carried on the hatch covers in dry cargo mode

- A31A2GT (General Cargo/tanker)

A General Cargo ship fitted with tanks for the additional carriage of liquid cargo.

- A31A2GX (General Cargo ship)

A single or multi deck cargo vessel for the carriage of various types of dry cargo. Single deck vessels will typically have box shaped holds. Cargo is loaded and unloaded through weather deck hatches.

- A31B2GP (palletized cargo ship)

A single or multi deck cargo ship loaded and unloaded by way of pallets lifts. There are no weather deck hatches.

- A31C2GD (deck cargo ship)

A vessel arranged for carrying unitized cargo on deck only. Access may be by use of a ro-ro ramp.

A schematic approach of the StatCode5v for all ship types is shown in the figure below.

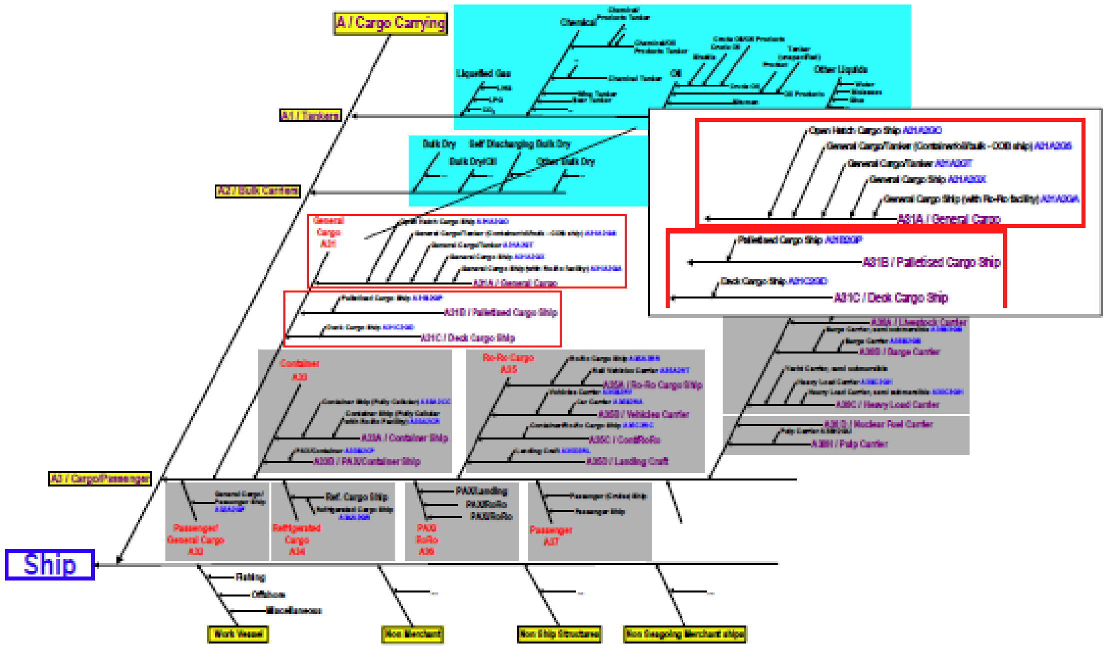


Figure 27: A diagram showing the structure of the StatCode5v coding system.

For the present analysis, all 7 General Cargo ship types were studied. It's worth noting however that the vast majority of General Cargo vessels in the sample are coded as A31A2GX (General Cargo ship). This can be assumed to be due to lack of more specific information.

7.1.2 Report fields

Sea-web™ database contains a plethora of data available. Most of the data appearing can be customized by the user. For this study, the data collected for each accident were:

- IMO Number

It is a unique identification number assigned to every vessel under the SOLAS convention. It was adopted in 1987 in an effort to 'enhance maritime safety, pollution prevention and to facilitate the prevention of maritime fraud'. This number is tied to a specific vessel, regardless of its name, flag or other indicative status. For this reason it is considered as part of a ship's identity (En.wikipedia.org, 2016d).

- Year of build

The year in which all mandatory new construction surveys were conducted. If there is a substancial delay between the date of construction survey and the date the ship commences its active service (date of commissioning), the later might also be used.

- Casualty date

The date in which the accident initiated.

- Incident number

A unique number assigned to each incident for the purpose of identification.

- Deadweight

It indicates the maximum weight a ship can safely carry, measured in tons. It is the sum of the payload, fuel weight, provisions, crew, fresh water and water ballast, excluding the ship's own weight (referred to as *lightship* weight). Roughly 80-85% of the deadweight is composed by the payload weight. As a result, DWT is a good indicator of the amount of cargo a vessel can carry (Papanikolaou, 2009).

- Gross Registered Tonnage

It measures the volume all enclosed spaces of a ship, calculated in "Registered Tons" (1gt=100 ft^3= 2.83 m^3). It is a key element of a vessel's identity and is used in a variety of calculations, such as defining the crew number, safety regulations applied, as well as various fees, port dues and taxes to be paid (En.wikipedia.org, 2016c).

- Classification society

Classification societies are non-governmental organizations responsible for imposing safety criteria to ships during all stages of their life-cycle, as well as maintaining their seaworthiness. They execute their task by establishing regulations and routinely surveying their vessels as to whether they comply. However, inspections are not only limited to ships. Shipping companies, shipyards, part manufacturers, maritime insurance companies, etc. are also liable to classification societies (Mylonopoulos, 2004).

- Flag State

Ships travel across the world. Admiralty law states that every vessel should be registered in a country. Flag state is part of a ship's identity and plays a major role in the way a ship operates, since it determines the regulations by which the ship must abide, performs inspections to ensure compliance and impose penalties in an event of non-compliance. The country of registration can be different from the state where the shipping/management company is incorporated (Mylonopoulos, 2004).

- Number of people killed

The number of people who lost their lives, including any third parties unrelated to the accident.

- Number of people missing

The number of people missing. For the scope of this study –and to be on the safe side- missing people were perceived as ‘dead’ in the calculations.

- Existence of oil pollution

Whether or not oil spillage occurred as a result of the accident. In cases where the ship is declared a total loss, oil pollution is considered positive, since the trapped quantity of oil in the tanks will –sooner of later- be released into the sea water as a result of corrosion and/or acting stresses.

- Geographic location

A text description of the area where the accident took place. Sea-web™ divides the world map into 30 geographic zones (Chrysavgis, 2011). The categorization is shown below.

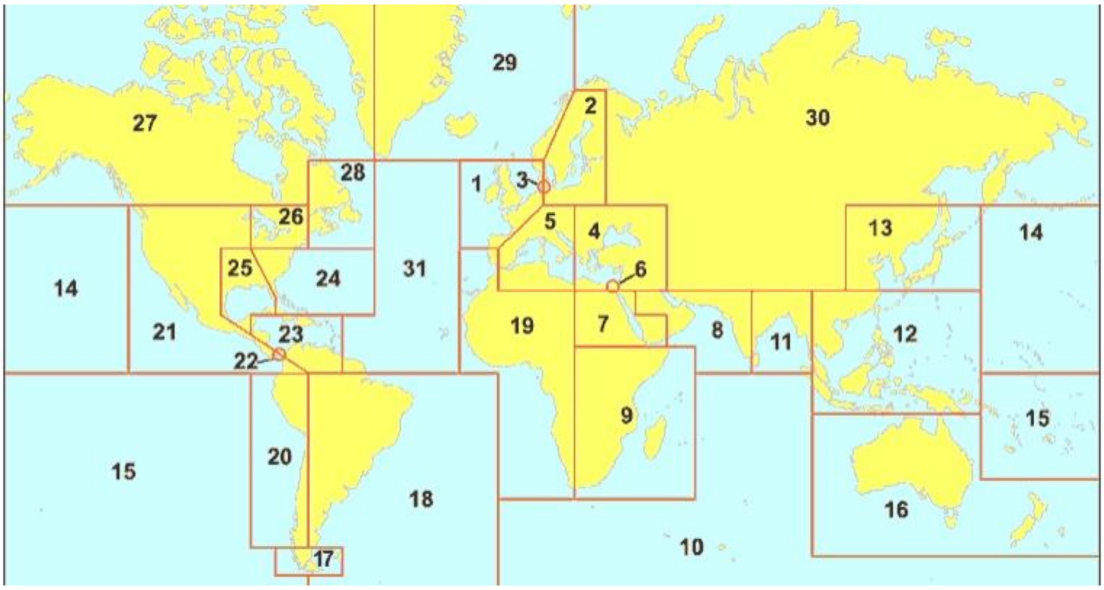


Figure 28: The world map divided in geographic zones. Sea-web™ uses this approach for coding location data.

- Marsden grid location

Marsden grid is a method used to divide the world map into consecutive rectangle areas, each one having a different number. It is widely used in meteorology as a way of defining different areas on a map. The grid is composed of latitude-longitude lines distanced at 10° intervals in both directions. According to the projection method used for mapping, the grid areas can appear to be squares (in plate carree projection) or rectangles of varying heights (in Mercator projection) (Chrysavgis, 2011). An example of a Marsden grid applied on a Mercator projection map is shown below. As someone moves away from the equator and closer to the poles, the rectangular areas elongate to the vertical direction.

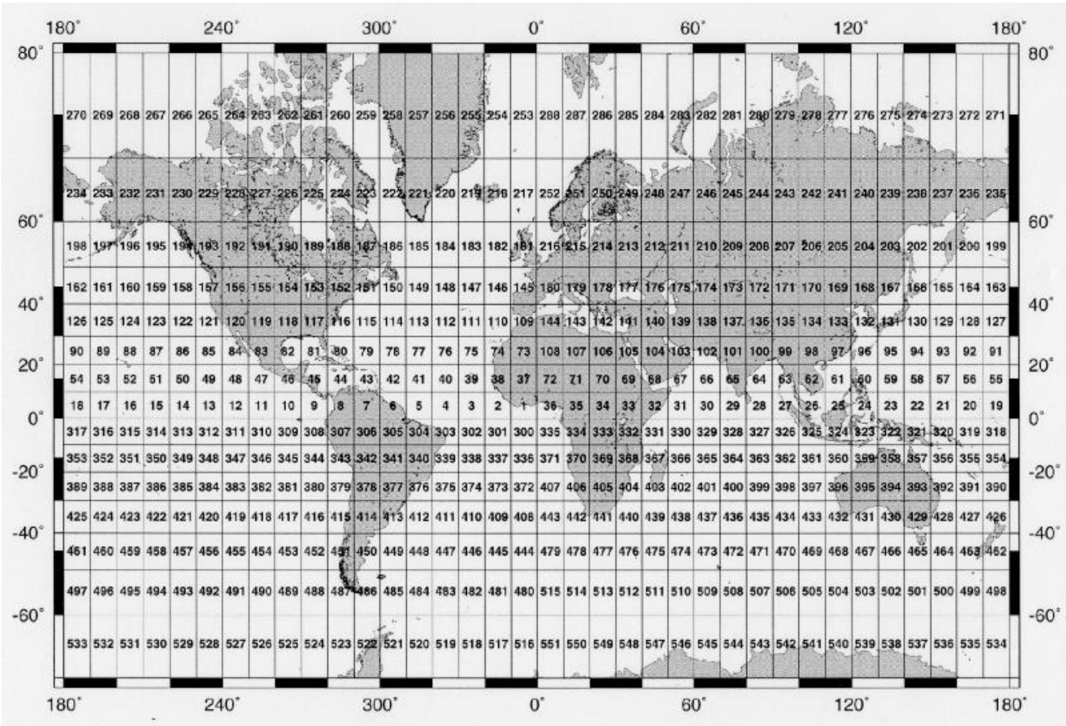


Figure 29: A Marsden grid divides the world map into rectangular areas, with each line distanced at 10 degree intervals both horizontally and vertically.

7.2 Ship classification by size and cause of failure

The statistical sample used in this report includes General Cargo vessels involving in accidents revolving around structural failures in hull, pipes and tanks. This excludes accidents due to collision/contact were the hull may be breached from an extraneous factor, such as another vessel, rock, etc. The casualty date was set from January 1st 1990 to December 31st, 2016. No size exclusion was made.

From the 3,752 accidents found on the Sea-web™ database, 417 were valid according to the criteria specified above. For the sake of convenience in data handling, 2 distinct categorizations took place.

a) According to size, vessels with less than 5,000 GT were classified as “Small”, whereas vessels larger than 5,000 GT where classified as “Large”.
b) In addition, according to the cause of the structural failure, vessels were grouped into those that failed due to *Corrosion* and those that failed due to *Crack.* The term crack implies any failure caused by reasons not relating to corrosion. These may include, failure due to an extreme loading condition, due to bad weather (ex. hogging-sagging), due to burst of piping under stress, etc.

As a result, four categories were created:

- Small vessels with corrosion-related failure (*small-corrosion*)
- Large vessels with corrosion-related failure (*large-corrosion*)
- Small vessels with strain-related (crack) failures (*small-crack*)
- Large vessels with strain-related failures (*large-crack*)

After the classes are established, a visual representation of all possible accident scenarios is created by the use of ETA.

The reason why ETA is preferred over FTA is that the accident has already manifested itself. Rather than focusing on its causes –which would require FTA- the purpose is to analyze the consequences. This can be done by multiplying the probabilities of each branch with the expected value of the consequences, expressed in proper units. In order to assess each probability, statistical analysis was performed on the casualty data collected from Sea-web™.

7.3 Parameters of interest

Hull

Depending on weather the initial failure took place on the hull structure or on the tanks or pipes, accidents were categorized in *hull: yes* and *hull: no*.

Starting point

This factor indicates the specific element on the hull in which the accident initiated. On a typical General Cargo cross-section one can distinguish 6 elements:

- Exterior deck plating
- Interior deck plating
- Side shell
- Floor
- Inner bottom
- Bottom shell

In the case of tanks and pipes, no further distinction takes place:

- Tanks
- Pipes

Location

This parameter has to do with the area of the vessel where the incident initiated. Three such locations are of importance:

- Fore Peak

The foremost part of the vessel, extending from the front to the collision bulkhead

- Cargo Space

The area in which cargo is placed. It lies between the Fore Peak and the Engine Room.

- Engine Room (E/R)

The area that extends from the transom to the head bulkhead. It’s the area in which the main engine and auxiliary systems are located.

Since only hull failures are of concern, the accommodation area is not included in the parametrization.

Progression

Whether the accident remained local (progression: no) or progressed to the failure of the entire cross section (progression: yes).

Loss Of Watertight Integrity (LOWI)

If a ship loses its water tightness and sea water breaks into the structure then the incident is classified as *LOWI: yes*.

There are 2 ways in which a ship can lose its watertight integrity:

a) Via a breach in the hull (ex. crack due to strain or corrosion). This can happen anywhere on the outer surface of the ship. Specifically in the bottom shell, side shell or the deck plating.
b) Via a tank/pipe leak from an open circuit system that comes into direct contact with sea water. For example, if a ballast system pipe bursts and flows water in the ship, the incident will be classified as LOWI: yes. In contrast, if a fuel pipe leaks then the flooding is not considered LOWI, since the system is not in direct contact with sea water.

Degree of Severity

As to the extent of the damage caused to the vessel, casualties are classified into 4 categories:

- Total loss

In this case the ship sinks or comes to a state where retrieval is impossible.

- Scrap

When the ship is deemed financially unadvisable and is sold for breaking up.

- Significant

An accident that caused substantial damage to property, loss of human life or environmental pollution.

- Minor

An accident that is small in extent and can be fixed by the ship's own crew with minimal intervention. Usually these types of accidents lead to relatively minimal damage to property and no human loss or environmental impact (such as a minor leak, etc.).

Each of the previously mentioned categories represents a possible outcome and is represented by a single branch on the event tree. The task is to assign probability and consequence values to each scenario. The product of these two numbers will give a risk value. Using the current parametrization, 336 possible scenarios were generated (288 scenarios for hull damage and 48 scenarios for tank/pipe damage). Further categorization would exponentially increase the number of possible scenarios, making the collection of data impossible in the context of the present study. It's worth noting that even after the addition of one extra node with two possible outcomes, the number of possible scenarios would double to 672. FSA is a labor-intense process were teams of experts work for several years to gather, categorize, process the data and generate useful results.

A collapsed diagram of the ET used is shown below. The parameters of interest are on top, with their respective values under them.

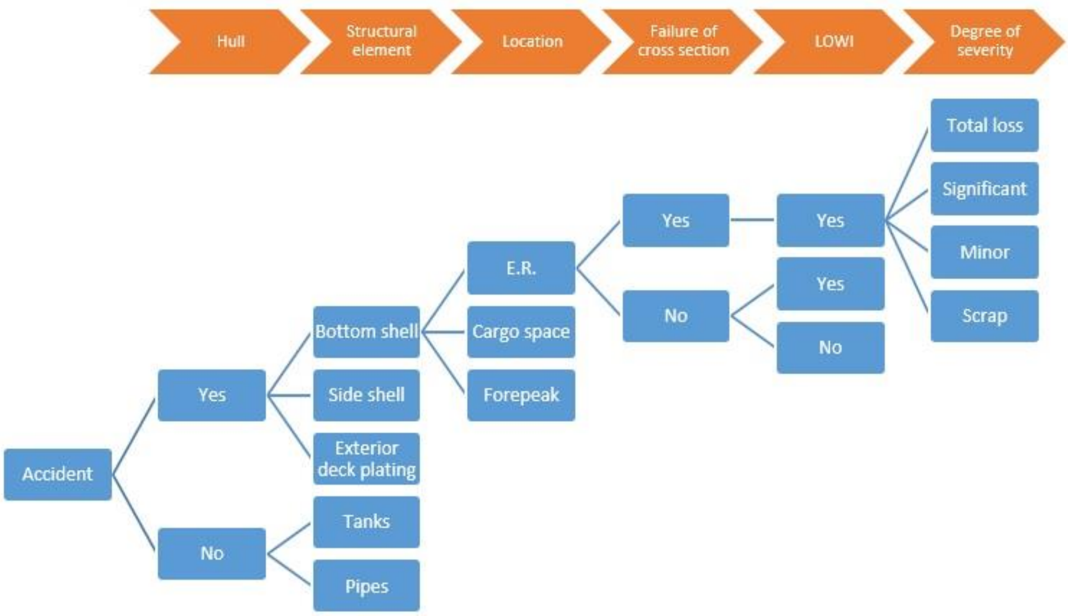


Figure 30: A collapsed version of the ET used in the study. The events follow a logical order.

The full sized (expanded) tree is too large. For this purpose it is included in the Annex and not in the main body of the thesis.

7.4 Quantification of risk

7.4.1 Quantification of probability

Accident scenario is the sequence of events that connects an initial event to the final consequence, by passing through all intermediate steps in a logical and chronological order. For example, a ship accident might be caused by heavy weather. This event might cause the vessel to sail adrift and hit a rock. After the collision, flooding can occur and can ultimately lead to adverse consequences, such as ship damage, fatalities or pollution. The event classification (initial, intermediate, final) can vary according to the scope of each study and the preferences of the authors.

For the purpose of risk analysis of shipping accidents, the following general model is proposed:

$$Risk = \sum_i \sum_j \underbrace{\Pr(Ca_i)}_{Cause\ model} \underbrace{\Pr\left(F_j | Ca_i\right)}_{Vulnerability} \underbrace{\sum_k Co_{jk} \Pr\left(Co_{jk} | F_j\right)}_{Consequence\ model}$$

In this formula, 3 different models can be distinguished:

- Cause model

This model uses various inputs in order to assess the probability of a certain *cause* to happen. A cause is an unwanted initial event that progresses through specific steps and can lead to the final consequence.

- Vulnerability

For an initial event to lead to a disaster, a vulnerability must also be present. For instance, heavy weather might set a ship adrift, but a vulnerability, such as weakened hull structure, must also be present for an accident to occur (hull breach, flooding and eventually total loss). Conversely, a vulnerability without a cause cannot lead to an accident. The purpose of the vulnerability model is to evaluate the probability of a certain vulnerability to be present, given a specific cause.

- Consequences

After a cause and a vulnerability are present, the accident initiates. Through a series of steps, it can lead to various consequences. The purpose of this mathematical model is to calculate the probability of a specific consequence occurring (such as Loss Of Life), given the accident and significant input parameters. For instance, a hull breach might lead to sinking under heavy weather conditions in an open sea. The same accident under normal weather and/or in coastal waters can only cause minor consequences. Finally, the probability is multiplied by a severity factor, in order to render risk values.

Mathematical formulas

The majority of safety studies assess risk in terms of 3 consequences, namely: Loss Of Life (LOL), Environmental Impact (EI) and Damage To Property (DTP). The general expression of the consequence model is:

$$P\left(Co_k \middle| F_j\right) = \frac{P(Co_i \cap F_j)}{P(F_j)}$$

The above formula represents the probability of the k-th consequence to happen, given that the j-th Failure has occurred. The formula can be applied to any combination of consequences and failure modes. In term of failure modes, only LOWI is studied. Each particular case is presented below:

- Loss Of Life

$$P(LOL|LOWI) = \frac{P(LOL \cap LOWI)}{P(LOWI)}$$

- Environmental Impact

$$P(EI|LOWI) = \frac{P(EI \cap LOWI)}{P(LOWI)}$$

- Damage To Property

$$P(DTP|LOWI) = \frac{P(DTP \cap LOWI)}{P(LOWI)}$$

Damage to property might refer to both Damage To Ship structure (DTS) and Loss Of Cargo (LOC). As a result:

$$DTP = DTS \cup LOC$$

By substitution, the probability formula becomes:

$$P(DTP|LOWI) = \frac{P([DTS \cup LOC] \cap LOWI)}{P(LOWI)}$$
$$= \frac{P[(DTS \cap LOWI) \cup (LOC \cap LOWI)]}{P(LOWI)}$$
$$= \frac{P(DTS \cap LOWI) + P(LOC \cap LOWI) - P(DTS \cap LOC \cap LOWI)}{P(LOWI)}$$

In order to check the accuracy of the above formulas, data from bulk carrier FSA was compared to independent calculations performed by these formulas. A sample of 250 vessels was taken from Sea-web™ database. The results were:

$$P(LOL|LOWI) = 15.4\%$$
$$P(EI|LOWI) = 39.61\%$$
$$P(DTP|LOWI) = 100\%$$

The values acquired from the FSA of bulk carriers (IMO, 2002a) are widely in accordance with the numbers above:

$$P(LOL|LOWI) = 20.17\%$$
$$P(EI|LOWI) = 44.64\%$$
$$P(DTP|LOWI) = 100\%$$

The FSA results were generated by the use of Event Trees for bulk carriers of more than 10,000 DWT.

$$P(LOL|LOWI) = \frac{N(LOL \cap LOWI)}{N(LOWI)}$$
$$P(EI|LOWI) = \frac{N(EI \cap LOWI)}{N(LOWI)}$$

Since no direct data was available for environmental pollution (oil spillage) it was assumed that $N(EI \cap LOWI) \geq N(TOTAL\ LOSS \cap LOWI)$. This assumption holds true, since all total loss accidents will eventually lead to oil spill. As a result, the probability of an oil spill due to LOWI was roughly calculated by:

$$P(EI|LOWI) = \frac{N(TOTAL\ LOSS \cap LOWI)}{N(LOWI)}$$

Finally,

$$P(DTS|LOWI) = \frac{N(DTS \cap LOWI)}{N(LOWI)} = 1$$

since $N(DTS \cap LOWI) = N(LOWI)$. This stems from the fact that DTS is a superset of LOWI (DTS⊃LOWI). That means that any LOWI accident automatically involves damage to property.

The following numbers were taken from the FSA of bulk carriers.

Table 3: Frequency data for Bulk Carrier accidents

$N(LOWI)$	$N(LOL \cap LOWI)$	$N(EI \cap LOWI)$	$N(DTS \cap LOWI)$
233	47	104	233

Existing differences in the values are due to the different databases used (Sea-web™ vs. LMIS) and the size of the sample used. It is impossible for the present study to include as many accidents as those included in an FSA, due to lack of workforce.

Ship Compartmentation

In order to gain greater insight as to the on-board location the LOWI accident occured, the ship is categorized into 3 areas:

- Engine Room

The area extending from the aft end of the vessel to the engine room bulkhead and from the keel to the main deck in the vertical direction. It contains the main engine and auxiliary systems of the ship.

- Cargo Space

It extends from the engine room bulkhead to the collision bulkhead in the longitudinal direction, and from the keel to the main deck in the vertical direction. It comprises the area where cargo is stored and it can be either continuous or separated by watertight bulkheads that create additional holds between them. Hatch cover failures are considered cargo space failures.

- Fore Peak

The foremost part of the vessel. The fore peak extends from the bow of the ship to the collision bulkhead. In the vertical axis, it extends from the keel to the main deck. The forecastle area is also classified as "fore peak".

As previously stated, the accommodation area is not included, since it cannot lead to LOWI accidents.

The areas are depicted in the general arrangement plan below.

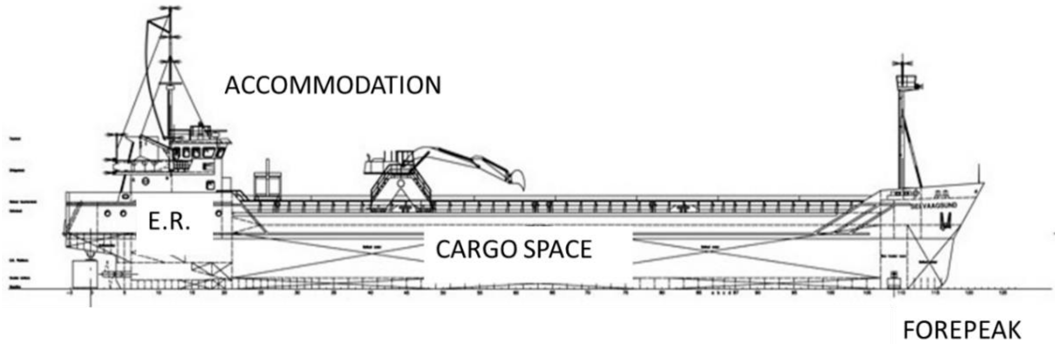


Figure 31: General arrangement plan for a General Cargo ship with the different areas shown.

Naturally, the total probability of a specific consequence is the sum of all the corresponding probabilities for each area of the ship.

$$Ship = Engine\ Room \cup Cargo\ Space \cup Fore\ Peak \cup Accommodation$$

$$P(LOL|LOWI)$$

$$= \frac{P([LOL_{E.R.} \cup LOL_{CARGO\ SPACE} \cup LOL_{FORE\ PEAK} \cup LOL_{ACCOMMODATION}] \cap LOWI)}{P(LOWI)}$$

$$= \frac{P(LOL_{E.R.} \cap |LOWI) + P(LOL_{C.S.}| \cap LOWI) + P(LOL_{F.P.}| \cap LOWI) + P(LOL_{ACC.}| \cap LOWI)}{P(LOWI)}$$

7.4.2 Quantification of consequences

For the risk to be calculated, both probability and severity must be known. Probability values were derived from frequencies taken from the statistical analysis. In some cases, the exact scenario was unknown due to lack of reported information, so assumptions had to be made to offset the lack of knowledge.

In terms of severity, a method for quantifying consequences has to be established. Again, assumptions have to be made to compensate for missing data.

It is decided that accidents will be studied in reference to 3 consequences, namely:

- Loss of life
- Environmental pollution

- Damage to property

1. Loss of life

An incident at sea might lead to injuries or deaths for any involved party. Since the study focuses only in accidents caused by structural failures on the ship itself, some accident categories are excluded. For instance, collision, contact, fire/explosion accidents are insignificant, as the failure in this case is caused by an extraneous factor. Because these accidents happen to the ship itself, most of the times no other parties are at steak except from the ship's crew.

Out of the 417 casualty reports studied all provided sufficient knowledge as to the number of people injured or dead. Some incidents (9) included missing people. After further research all of the missing cases were proved to be dead and were added to the fatalities.

Injuries were converted into fatalities by the following transformation:

- 10 severe injuries are considered equivalent to 1 fatality. As a result, 1 severe injury is equal to 0.1 fatalities.
- 100 minor injuries are considered equivalent to 1 fatality. Consequently, 1 minor injury is equal to 0.01 fatalities.

2. Environmental pollution

The term 'environmental pollution' refers to oil outflow to the sea. No other pollutants were considered in this study, such as hazardous cargo or pollution caused by the metal structure of the ship. Since General Cargo vessels are used for dry cargo transportation, the only way in which oil might be released is from the fuel tanks where it's stored (storage and service tanks).

Since many reports had *unknown* oil pollution status (154 out of 417 reports), the following convention was used:

- In the cases where oil outflow was reported by quantity (3 cases), it was taken as such.
- All total loss accidents were assumed to have an oil outflow value of 120 tones. This is so because any oil left in the tanks will eventually spill out due to the harsh conditions in the sea bed.
- In any other case that did not lead to total loss (significant, minor or scrap) and pollution was reported, a value of 50 tones was assumed.

3. Damage to property

Damage to property refers to the monetary cost of repairs after an accident has occured. Unfortunately, no reports stated the costs associated with damage repairs. As a result, the following assumptions were made:

- In the case of total loss (sinking) of the ship, the cost is calculated by the price of the newbuilding adjusted to 2016 values. The function used for this transformation is derived from IACS FSA study for General Cargo ship safety (IMO, 2010c) and is based on statistics from 142 ships under 25,000 DWT between the years 2000 and 2009, adjusted to 2010 USD values. Afterwards, the output was readjusted to 2016 USD values by the use of historic inflation charts. A function was then created by means of statistical regression.

The formula can be used in our case, since the assumptions in which it was based are satisfied. Specifically, only 4 of the ships in the reports exceed the 25,000 DWT threshold.

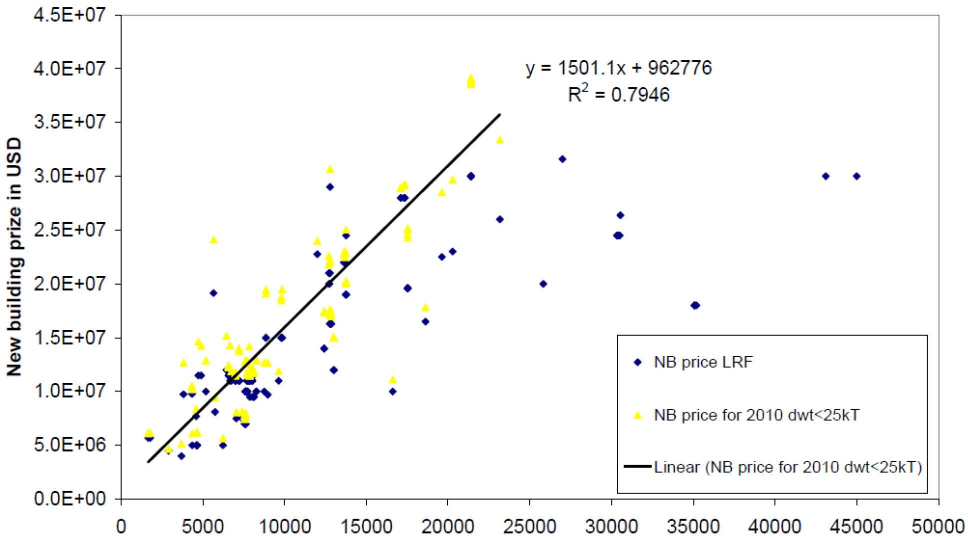


Figure 32: New building price vs. DWT diagram. This chart was generated by the use of linear regression on real data.

- Significant accident costs were calculated differently for each ship size. For small ships (under 5,000 GT) an average cost of $ 120,000 was assumed. For large vessels, the cost rose to $ 300,000. These values were derived from IACS FSA study for General Cargo ships in the event of hull damage.
- Accidents that led to break up (scrap) were calculated by the newbuilding price (as in the case for total loss), minus the income received from the scrapyard. This was evaluated at 250$/ton from Clarksons scrap price over the past year (average value) (Clarksons, 2016).

The values used for the quantification of the consequences, as well as the new building price vs. DWT diagram are identical to those used in the FSA study for General Cargo ships (IMO, 2010b; IMO, 2010c).

7.5 Zero event tree branches

Many accident scenarios lead to zero probabilities. This is because no accident scenarios of these types were found. This is a result of several factors, such as:

- Underreporting

Many minor accidents are left unreported, especially in General Cargo vessels. This is done in order to avoid penalties, as was previously discussed in chapter 6.2.2.

- Insufficient data

There is lack of sufficient data to work on. Specifically, from 3,752 accidents related to structural failures on General Cargo ships, only 417 were significant. According to the event tree however, there are 384 possible scenarios. Under these conditions, it is expected that some scenarios will have zero frequencies.

- Assumptions

Database reports provide insufficient information in specific aspects of the accident. For instance, the structural element in which the accident started (bottom shell, side shell, etc.) was clearly mentioned in under 1% of the reports. As a result, assumptions had to be made to compensate for insufficient data. These assumptions were made on the basis of logic and the principles of mechanics, leaving some branches with zero values. For instance, when a ship's bottom cracked due to heavy weather, physics dictated that the outer bottom shell was ruptured at first (and not the interior plate) since bending moments maximize at further distances from the neutral axis. This resulted in zero frequency for interior bottom plate crack failures.

8. Results

In the present chapter the results of the study are apposed. The chapter is divided in 2 segments: First, a general outlook presents statistics concerning General Cargo ship structural accidents in general. Those may be: geographic areas more prone to accidents, size of the ships involved, etc. The second part goes into greater detail and provides more detailed information about the accidents, such as the location of the damage, the progression of the accidents, the outcome, etc.

8.1 General outlook

Geographic allocation of accidents

Data analysis on accidents by geographic location shows that not all areas are equally prone to accidents. Some locations accumulate more casualties than others. The table below summarizes the findings.

Table 4: Top world locations in terms of accident rates for General Cargo ships.

Location	Percentage of accidents [%]
Br.Isles, N.Sea,E.Chnl,Biscay	23.28
E.Mediterranean & Black Sea	13.75
South China & East Indies	13.08
China, Japan & Korea	8.87
W.Mediterranean	5.76
TOTAL	64.75

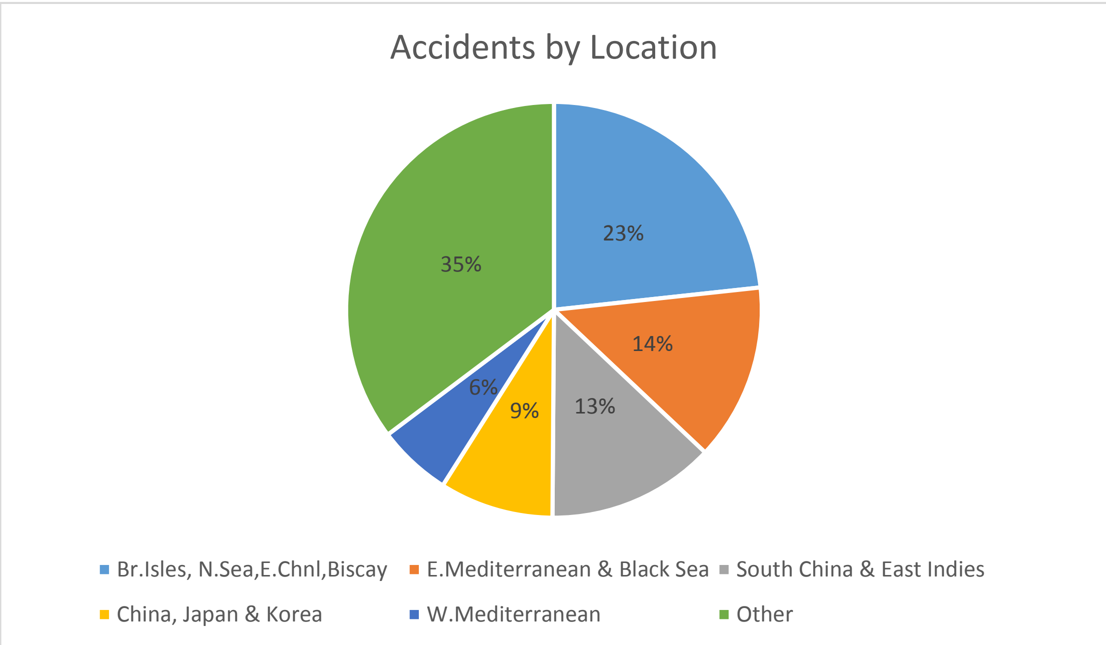


Figure 33: Pie chart created from the data of Table 4.

Using Marsden grid representation, the results are depicted below.

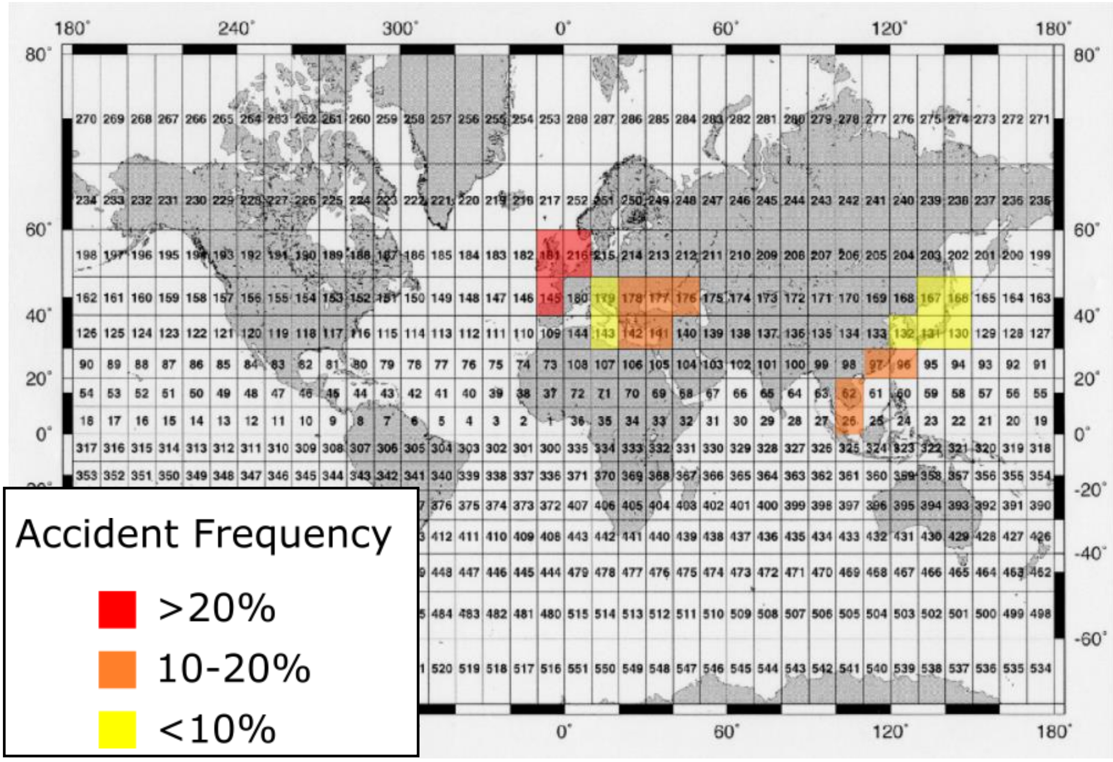


Figure 34: A Marsden grid showing the top locations most prone to General Cargo structural accidents, according to the findings of the study.

The previous statistics seem to be in agreement with similar studies. For instance, '*15 Years of Shipping Accidents: A review for WWF*' from Southampton Solent University highlighted the same 4 locations as most prone to shipping accidents for cargo ships for the period 1999-2011.

Furthermore, Chrysavgis (2011) lists the same areas as having the highest accident rates for General Cargo ships for the period 1995-2010.

The results are summarized in the chart below. All 3 studies rank the same top 4 locations as more prone to accidents, regardless of the relative differences in rates. The fifth location is different for each study.

It's worth noting that this study's results are closer to Chrysavgis (2011), which is to be expected since both studies are exclusive to General Cargo ships. SOLENT University's study, on the other hand, includes all cargo vessels.

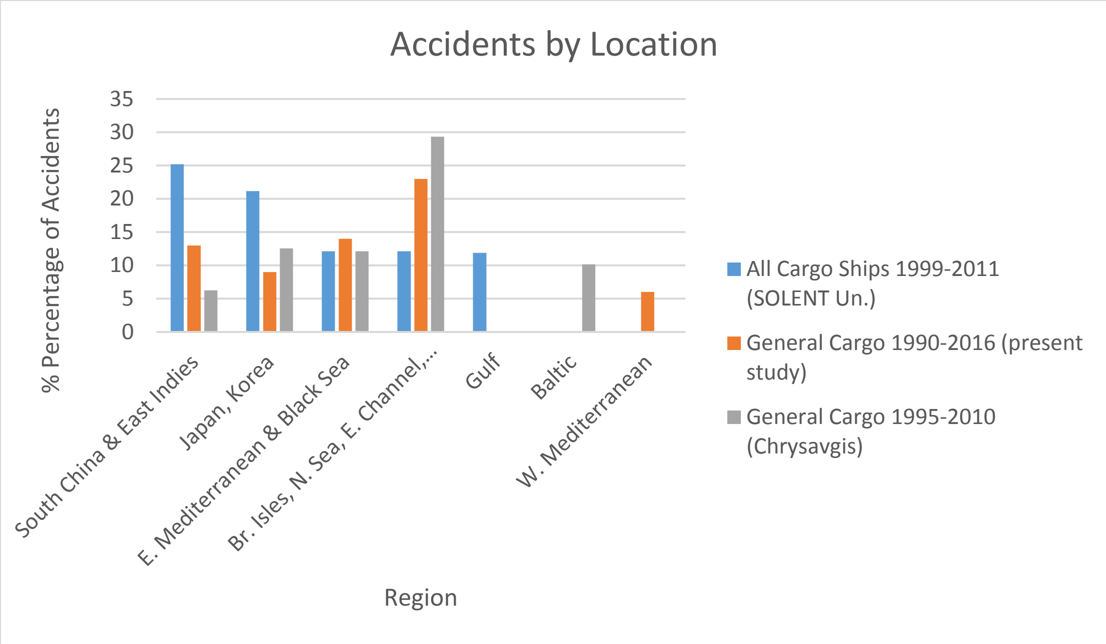


Figure 35: Accident rates by geographic location for 3 different studies.

Ships by size

Casualty data gathered from Sea-web™ indicated that 27.37% of the accidents happened on large ships (vessels of over 5,000 GT), whereas 72.63% of the accidents occurred on small ships (those under 5,000 GT). The exact allocation of the number of casualties recorded for each GT bracket is shown below.

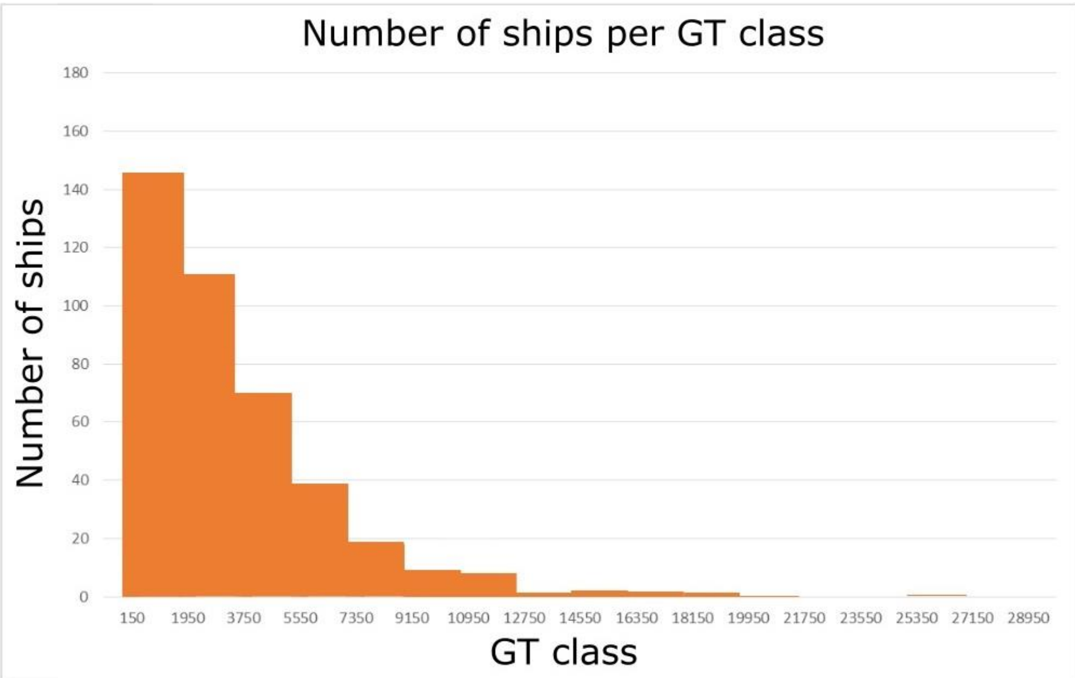


Figure 36: Number of ships by GT bracket. One can clearly see that the sample is skewed towards smaller vessels.

Operational area

First of all, the vast majority of structural failure accidents happen on the open seas (80.6%), while only a small percentage (19.4%) occurs on coastal waters, such as harbors, rivers/canals, straits, etc. This can be explained by the nature of these accidents and the time exposure a ship gets to each environment. Specifically, structural failures are mostly realized in open seas, since higher strains in the structure are most likely to occur there (for instance, due to hog-sag moment fatigue). This is backed up by the fact that many of these accidents happened in heavy weather (96.3%), whereas only 3.7% happened during calm weather. In addition, the time a ship spends traveling on open sea is considerably larger than the time spent in harbor or in canals.

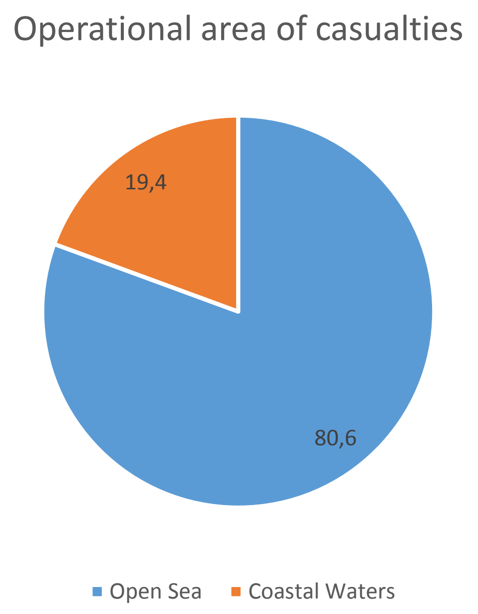


Figure 37: Operational area for General Cargo ship accidents.

Daytime

As to the time in the day when the accidents occur, one would expect insignificant differences. Indeed, casualties at day are somewhat more than those at night (59.2% versus 40.8%). This difference is expected to narrow down if we account for the large number of underreported casualties (only 16.7% of casualty reports included time).

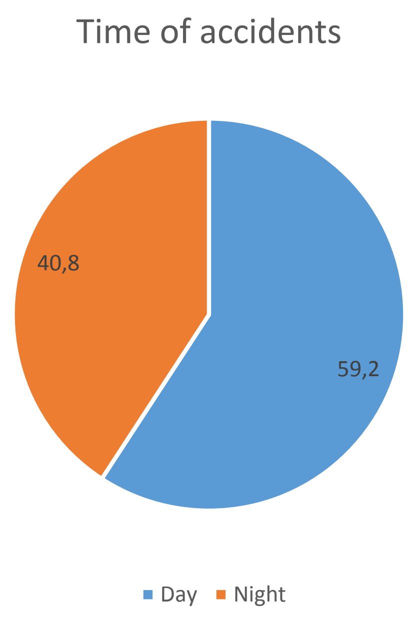


Figure 38: Time of accidents.

Classification societies

Another interesting fact is that 93.4% of the ships involved in casualties belong to an IACS accredited classification society, while only 6.6% are non-IACS members. This number can cause misinterpretations if not put into the right context. One of the major issues of the maritime industry is underreporting. Especially in non-IACS accredited classification societies, the issue takes gigantic proportions. Moreover, flag state and classification society might change several times during the lifespan of a ship. These changes cannot be monitored easily and result in outdated databases. For instance, a vessel recorded as IACS could belong to a non-IACS society at the time of the accidents

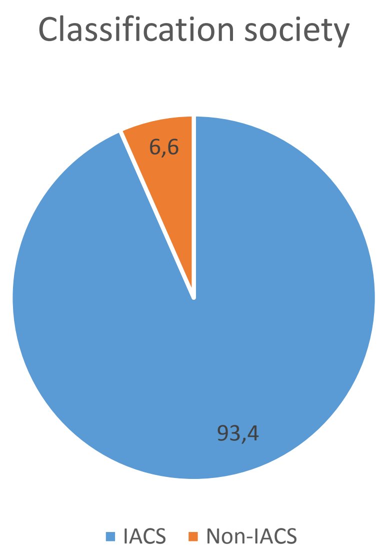


Figure 39: Classification society distribution.

Weather

Weather plays a major role in both the initiation and the outcome of an accident. 36.93% of the reported accidents happened under normal weather, whereas 63.07% happened under heavy weather. This can be explained by the fact that harsh weather (storm, hurricane, freezing conditions, etc.) increases the likelihood that an accident manifests itself. Moreover, it increases the severity of its results.

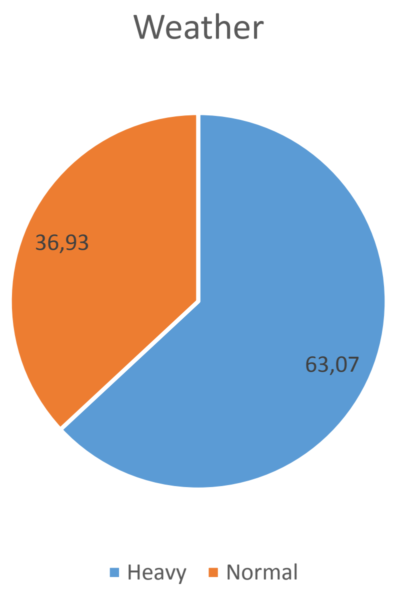


Figure 40: Weather distribution.

Loading condition

In regard to the loading condition of the vessel, 88.8% of the accidents happened while the ship was loaded. Only 11.2% of the incidents happened on ballast condition. This can be explained by the strains present in a loaded vessel, which are much more severe than those on an empty ship. Higher draft also means larger surface in which water pressure acts, while cargo itself can create unwanted bending moments in the hull structure. It’s not unusual for a combination of these factors to act simultaneously and lead to a destructive result. For instance, heavy weather might cause cargo to shift which can aggravate the strains already present in the structure, ultimately leading to fracture of the hull.

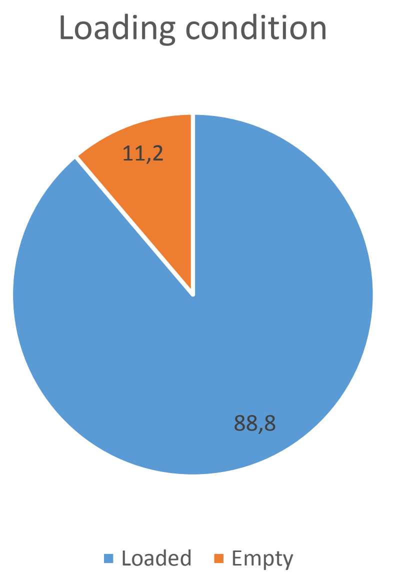


Figure 41: Ship's loading condition at the time of the accident.

8.2 Detailed analysis

Below is the detailed analysis for each ship class. The categorization of the vessels in *small* and *large* according to their GT simplifies the process of categorizing data and displaying useful conclusions.

8.2.1 Small vessels (under 5,000 GT) with corrosion

The case of small vessels with corrosion-related casualties numbered 80 incidents out of the 417 casualties for a period from January 1st, 1990 to December 31st, 2016. This translates into 19.18% of all structural failure accidents for General Cargo ships. In detail:

Intermediate events

1. **Corrosion occurrence in hull**

Hull accidents represent the vast majority. 87.5% of corrosion-related failures on small vessels happened on the hull structure, while only 12.5% occurred in tanks and pipes. This difference can be explained by the difference in space each category takes, as well as the environment in which it operates. The hull gets in direct contact with sea water, a highly corrosive substance. On the other hand, pipes and tanks are sealed from the weather since they are confined inside the vessel.

2. **Starting point of failure**

Hull accidents were divided equally between bottom shell and side shell plating (44.29% and 40% respectively). In contrast, exterior deck plating seems to account for only 15.71% of hull accidents. This can be due to the fact that corrosion is a localized phenomenon that is most likely to occur in areas that come in contact with the corrosive environment and are under significant stress.

Non-hull accidents were equally divided between tanks and pipes (50% each).

3. **Accident location**

As to the location of the hull accidents, cargo space has the highest cumulative frequency for all 3 starting points (51.43%), engine room follows with 40%, whereas the fore peak area comes last with a large difference (8.57%). An explanation might be that cargo space takes up much more area than the fore peak or the engine room.

Non-hull accidents were exclusively located in the engine room area. This is due to the fact that most tanks and piping systems are located there.

4. **Progression of Damage**

Almost all accident scenarios led to localized failures (ex. tear in hull), as opposed to failure of the entire cross section. Propagation of damage was not usual and in the vast majority of cases the damage stayed localized. The only case were the cross section collapsed and the vessel was lost was due to extensive corrosion on the side shell of the engine room (scenario probability: 1.25%). The remaining 98.75% of the incidents led to localized failures and no total loss of the vessel.

All tank and pipe accidents led to leaks. This is because for a tank or pipe to fail due to corrosion, stress must be applied in the troubled area as well. This stress usually stems from liquid pressure contained in the tank/pipe. Moreover, non-leaking bursts are usually left unreported since they are of minor severity.

5. **Loss Of Watertight Integrity (LOWI)**

In the event of cross section failure (1 scenario) LOWI obviously followed with a 100% chance. On the other hand, local damages can or cannot lead to LOWI. Most of the times (98.75%), local hull accidents did lead to LOWI.

In the case of tanks, no LOWI was recorded, since leaks from tank liquid inside the ship do not compromise the ship's watertight integrity. For instance, a ballast tank fracture from the inside of the ship is not considered LOWI, for the reason that the spilled water quantity is already in the ship and so the vessel maintains its water tightness.

Pipes however can lead to LOWI if the burst duct is in direct contact with the outside sea water. This was the case for 20% of pipe-related accidents.

6. **Degree of Severity**

Most hull accidents were classified as "significant" (90%), followed by accidents that led to "scrap" (5.71%), then "minor" (2.86%) and finally "total loss" (1.43%).

Most non-hull accidents were "significant" (60%), 30% led to "scrap" and 10% were "minor". No total loss stemmed from such casualties.

Consequences

1. **Loss of Life**

Only 2 accidents had reported fatalities (one with 2.4 and another with 0.1 fatalities). Multiplication by the respective probabilities gives a cumulative risk value (Potential Loss of Life-PLL) of 0.2413 lives. As a result it is safe to conclude that small vessel accidents from corrosion do not lead to fatalities.

2. **Environmental Impact**

Only one report stated pollution. Since no value for oil outflow was reported, an average quantity of 120 tones was assumed. This gives 1.5 tone of potential oil outflow (or Potential Environmental Impact-PEI). The scenario which resulted to the oil outflow was a total ship loss. In this case the author assumed that the oil would eventually be spilled from the tanks due to the harsh conditions on the sea floor (corrosive environment and high pressure).

3. **Damage to Property**

Damage to property was calculated for the cases of total loss, significant accident or scrapping. In total loss scenarios, the price of the newbuilding is assumed as cost. This is given as a function of GT adjusted in 2016 monetary value. Scrapping cost is the total value of the ship (as calculated for total loss) minus the income received from the scrapyard. This was calculated to 250$/ton, an average of present year’s steel price fluctuations. Finally, significant accidents are priced at $120,000 for small vessels.

With that in mind, calculations assess the monetary risk from damage to property to be $685,424 or $0.69 million

8.2.2 Large vessels (over 5,000 GT) with corrosion

Large vessels with corrosion-related accidents numbered only 30 cases out of 417. This is because: a) Large vessels are significantly less than small ones (26.62% versus 73.38%) and, b) Corrosion accidents are less frequent than fracture accidents (again 26.62% versus 73.38%). In detail:

Intermediate events

1. **Corrosion occurrence in hull**

The vast majority of these accidents happened in the hull structure (87.1%) in contrast to non-hull accidents (12.9%). The large difference can be explained by the highly corrosive sea water that comes into contact with the hull, whereas tanks and pipes are concealed inside the structure. In general, these numbers are very similar to those for corrosion in small vessels

2. Starting point of failure

Side shell seems to be the most frequent starting point of hull failures (40.74%), followed by the bottom shell (33.33%) and the exterior deck plating (25.93%). This can be attributed to the fact that both the side shell and the bottom shell come in direct contact with the sea, whereas the deck does not. However, due to lack of sufficient data (only 30 reports for this category) the numbers do not perfectly represent the reality and are heavily skewed by minor changes in reports. Taking this into consideration, they are closely related to the statistics of small vessel corrosion accidents.

Again, non-hull accidents between tanks and pipes were equally distributed (50% for each category).

3. Accident location

Cargo space presented the highest cumulative frequency among starting points (70.37%), engine room followed (22.22%) whereas the fore peak area came third with 7.41%. Similarly, those numbers could be attributed to the fact that cargo space is much larger in comparison to the fore peak or the engine room. It's worth noting that for the case of bottom shell failures, no accidents in fore peak were reported (0%).

Non-hull accidents were exclusively located in the engine room area, since tanks and pipes are mainly located there.

4. Progression of Damage

Only one scenario led to failure of cross section and the eventual total loss of the vessel (6.45%). The remaining 93.55% of the accidents led to localized failures with or without LOWI.

Similar to small vessels, all tank and pipe accidents were related to leaks.

5. Loss Of Watertight Integrity (LOWI)

All hull accidents included LOWI (100%) by demand.

On the other hand, not all tank accidents led to LOWI by definition. As previously stated, internal tank leaks are not considered LOWI since the ships water tightness is not compromised.

Pipe accidents also did not lead to LOWI. This is due to the fact that only closed circuits were burst and no outside water entered the structure.

6. Degree of Severity

The majority of hull accidents were classified as "significant" (81.48%), followed by accidents that led to "scrap" (11.12%) and finally "total loss" (7.40%). No "minor" incidents were reported (0%).

All non-hull accidents were "significant" (100%).

Consequences

1. **Loss of Life**

One incident led to loss of life (1 fatality). Multiplication by the respective probability gave a cumulative risk value (Potential Loss of Life-PLL) of 0.1290 lives. As a result, large vessel accidents due to corrosion rarely lead to fatalities.

2. **Environmental Impact**

Only one accident led to pollution (the case of total loss). Since no value for oil outflow was reported, an average quantity of 120 tones was assumed. Risk calculation gave 7.7 tons of potential oil outflow (or Potential Environmental Impact-PEI). One can notice that even though oil outflow remains the same (120 tones), in the case of large ships there is a greater risk of oil pollution, since it is more likely for a large vessel to sink.

3. **Damage to Property**

Using the same approach as before, the risk of damage to property is estimated to be $3,182,634 or $3.18 million.

8.2.3 Small vessels (under 5,000 GT) with cracks

Crack-related accidents are more common than corrosion-related ones. Moreover, small vessels are greater in number compared to large ones. As a result, this category is by far the most heavily represented, with 227 accidents out of 417 (54.44%). Due to the existence of sufficient data for this category, it is expected to acquire high quality statistical information is expected.

Intermediate events

1. **Occurrence in hull**

Hull-related casualties represented 89.38% of crack-related accidents in small vessels. The remaining 10.62% was comprised by non-hull accidents (tanks/pipes). This large difference could be explained by the fact that the hull structure is subject to far greater stresses during a ship's operation, such as dynamic forces from waves and wind. These forces are extremely severe in magnitude. Their periodicity contributes to stress fatigue, a phenomenon that amplifies the catastrophic effects on the structure. Tanks and pipes, on the other hand, are safely confined within the vessel and, overall, they receive lower stresses.

2. **Starting point of failure**

As to the starting point of the failure, crack accidents in hull mostly occurred at the bottom shell (46.54%), followed by the side shell (39.6%) and finally the exterior deck plating (13.86%).

Non-hull accidents were almost equally divided among tanks and pipes (45.83% and 54.17% respectively).

3. Accident location

By far, engine room seemed to have had the largest frequency among crack accidents in small vessels (62.20%). Cargo space followed with 30.32%, while fore peak accounted for only 7.48% of the crack incidents.

As expected, non-hull accidents only occurred in the engine room area (100%).

4. Progression of Damage

4.89% of the hull incidents led to failure of cross section and eventual total loss of the ship. The remaining 95.11% led to localized failures.

5. LOWI

In the case of cross section failure LOWI obviously followed with a 100% probability. In contrast, localized failures do not necessarily lead to LOWI. Hull accidents with local failures had an 83.16% chance of leading to LOWI.

As mentioned, tank leaks cannot lead to LOWI.

Pipes, on the other hand, presented a 30.77% chance of LOWI and 69.23% chance of maintaining watertight integrity.

6. Degree of Severity

76.93% of hull-related accidents were “significant”, 5.79% led to “scrap” and only 1.77% were “minor”.

Non-hull accidents were “significant” (8.85%) and “scrap” (1.77%). No accidents of this type led to total loss or were of “minor” severity. Again, minor incidents are usually left unreported.

Consequences

1. Loss of Life

Research found 8 incidents involving fatalities. Of those incidents, all but one had less than 1 fatality. One accident led to 7 fatalities. Risk calculation gave a PLL value of 0.4062 fatalities, a value larger than that for corrosion-related accidents, both in small and large ships.

2. Environmental Impact

Pollution from such casualties was reported in 10 incidents. Roughly 4.42% of crack-related accidents in small ships led to oil pollution. This corresponds to a PEI value of 18.93 tons of oil.

3. Damage to Property

The potential damage to property (PDTS) for this type of accidents was estimated to be $754,643 or $0.75 million.

8.2.4 Large vessels (over 5,000 GT) with cracks

The research gave 80 accidents in this category out of the 417 accidents. This accounts for 19.18% of all significant accidents of the sample. Larger vessels are underrepresented since smaller ones dominate the General Cargo world fleet.

Intermediate events

1. **Occurrence in hull**

Hull-related accidents accounted for 87.5% of the total accidents in this category. Non-hull (tanks/pipes) accidents were the remaining 12.5%. This difference could be explained by the amount of stress each category undergoes. The hull receives much higher stress -both static and dynamic, which can lead to fatigue- whereas tanks and pipes operate in a much more predictable environment with less –if any- cyclic stresses.

2. **Starting point of failure**

Hull accidents were most likely to initiate from the side shell (51.43%), followed by the bottom shell (34.29%) and the exterior deck plating (14.28%).

Again, tank and pipe accidents were almost equally distributed in number (40% and 60% respectively). The 10% difference is insignificant in this case, since the number of non-hull accidents is 10 and statistical analysis can be widely affected by even one single change in data.

3. **Accident location**

In the case of bottom and side shell accidents, cargo space presented the highest frequency (54.17% and 50% respectively), followed by the engine room (41.67% and 36.11%) and the fore peak (4.17% and 13.89%). The landscape changes for accidents that initiated at the deck plating. In such case, 60% of the incidents took place at the fore peak, followed by 30% in the cargo space and only 10% in the engine room area.

Non-hull accidents happened entirely at the engine room area (100%).

4. **Progression of Damage**

None of the accidents led to failure of cross section and total loss of the ship. All incidents led to localized failures instead.

5. **LOWI**

80% of hull accidents led to LOWI, while 20% did not.

No tank incidents led to LOWI.

Pipe-related casualties had a 16.67% chance of leading to LOWI and an 83.33% chance of preserving the water tightness of the vessel.

6. **Degree of Severity**

88.57% of hull-related casualties were "significant" and 11.43% led to "scrap". No "total loss" or "minor" accidents were reported.

Tank and pipe incidents were classified as "significant" (80%) and "scrap" (20%). Again, no "total loss" or "minor" status was reported.

Consequences

1. **Loss of Life**

Only 1 fatal incident was reported for this class (2.1 fatalities). This led to a PLL value of 0.0263 fatalities.

2. **Environmental Impact**

Pollution was reported in 3 cases (3.75% of crack accidents in large vessels). This translated into a PEI value of 11.25 tons of oil.

3. **Damage to Property**

The potential damage to property (PDTS) was estimated to $2,835,738 or $2.84 million.

8.2.5 Comparison of results

In this section, a comparison between the four classes is performed. Each category is judged by its consequences, such as loss of life, environmental impact and damage to property. The 4 classes are:

- Small vessel (under 5,000 GT) with corrosion-related accidents
- Large vessels (over 5,000 GT) with corrosion-related accidents
- Small vessels (under 5,000 GT) with crack-related accidents
- Large vessels (over 5,000 GT) with crack-related accidents

Corrosion accidents

Corrosion is dangerous to any type of load bearing metal structure. It acts by deteriorating the material's physical properties, "eating away" the metal surface and reducing the thickness of the structure. Obviously, a thinner material can withstand less stress. Should preventive measures not be taken, the stress threshold continues to diminish, until the load becomes too much for the structure to bear, leading to collapse.

Ship corrosion presents a major issue for the maritime industry by adding costs to the construction, maintenance and repair aspects of a vessel's life cycle. Moreover, it poses an issue of environmental concern. Corrosion eats away the metal structure of the ship by altering its chemical composition. The newly formed by-product is slowly but steadily discharged at sea, polluting the environment.

Below is a table and its respective chart containing statistical data for corrosion-related accidents in both small and large General Cargo vessels.

Table 5: Corrosion-related accident severity by ship size.

Degree of Severity	Small vessels (under 5,000 GT) [%]	Large vessels (over 5,000 GT) [%]
Total Loss	1.25	6.45
Significant	86.25	83.86
Minor	3.75	0
Scrap	8.75	9.69

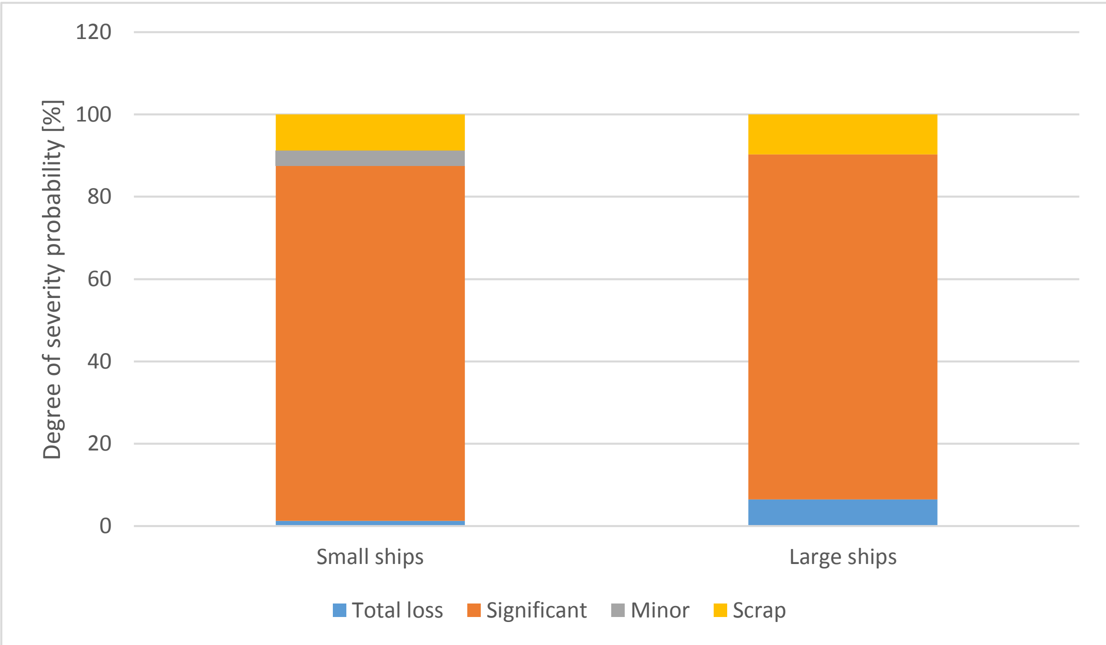


Figure 42: Bar chart based on the data of Table 4.

The above chart indicates that "significant" and "scrap" classified accidents have equal probabilities among small and large vessels. Differences are insignificant. On the other hand, "total loss" accidents in large vessels are 5 times more likely to occur than in small vessels. This could be due to the fact that the effect of corrosion increases as the contact surface increases. As a result, larger ships experience corrosion more severely.

Finally, "minor" incidents are non-existent in large ships, whereas in small ships they have a 3.75% probability of occurrence.

Cumulative risk comparison

Total risk values for each consequence give a more accurate view of the dangers posed by corrosion-related accidents. This is so because both probability (frequency) and severity (consequences) are included in the calculations. The following tables summarize the risk values for each consequence type (loss of life, environmental pollution, damage to property) according to accident severity and ship size.

Table 6: Probabilities, expected values and cumulative risk for fatalities due to corrosion-related accidents.

	Small ships			Large ships		
Degree of severity	Fatality probability [%]	Average lives lost [fatalities]	Cumulative risk value [fatalities/ship-life]	Fatality probability [%]	Average lives lost [fatalities]	Cumulative risk value [fatalities/ship-life]
Total loss	0	-	-	0	-	-
Significant	50	2.4	0.24	100	1	0.1290
Minor	0	-	-	0	-	-
Scrap	50	0.05	0.0013	0	-	-
Grand total	2.5	-	0.2413	3.23	-	0.1290

Table 7: Probabilities, expected values and cumulative risk for oil pollution due to corrosion-related accidents.

	Small ships			Large ships		
Degree of severity	Pollution probability [%]	Average oil pollution [tones]	Cumulative risk value [tones/ship-life]	Pollution probability [%]	Average oil pollution [tones]	Cumulative risk value [tones/ship-life]
Total loss	100	120	1.50	100	120	7.74
Significant	0	-	-	0	-	-
Minor	0	-	-	0	-	-
Scrap	0	-	-	0	-	-
Grand total	1.25	-	1.50	6.45	-	7.74

Table 8: Probabilities, expected values and cumulative risk for damage to property due to corrosion-related accidents.

	Small ships			Large ships		
Degree of severity	Damage probability [%]	Average cost [million $]	Cumulative risk value [million $/ship-life]	Damage probability [%]	Average cost [million $]	Cumulative risk value [million $/ship-life]
Total loss	1.3	3.51	0.04	6.45	15.2	0.98
Significant	89.61	0.12	0.10	83.87	0.3	0.25
Minor	0	-	-	0	-	-
Scrap	9.09	6.15	0.54	9.68	20.15	1.95
Grand total	100	-	0.69	100	-	3.18

Crack accidents

Cracks are the most common structural failures. They are caused by inadequate design and/or improper operating conditions. By definition, a crack is the separation of bonds between atoms that is caused by excessive mechanical stress. The mechanisms that lead to fractures may vary. Metal materials can crack under the following processes:

- Low temperature cracking due to tensile stress
- High temperature cracking under tensile stress
- Cracking due to fatigue
- Cracking due to corrosion

The last category, cracking by corrosion, was studied in a previous section. Accidents of this type were perceived as corrosion-related. The other 3 categories are covered in this section. The following examples highlight the applicability of each category in real-life accidents:

‘A poorly loaded vessel can experience severe bending stresses. Under these forces a section might collapse under static tension in low temperatures’.

‘High combustion pressures in the main engine lead to increasing bending stress applied to each crankshaft throw. This can lead to fatigue cracking of the crankshaft due to fluctuations of stress applied to the component’ (Marine Engineering Study Materials, 2017).

‘Poor coating conditions can lead to corrosion in the shell plates that deteriorate the metal surface. If proper measures are not taken the hull can be torn under stresses that would otherwise be acceptable’.

A large number of accidents are caused by cracking. Below follows a table and its respective chart summarizing statistical data for crack-related accidents in small and large General Cargo vessels.

Table 9: Crack-related accident severity by ship size.

Degree of Severity	Small vessels (under 5,000 GT) [%]	Large vessels (over 5,000 GT) [%]
Total Loss	4.87	0
Significant	85.84	87.5
Minor	1.77	0
Scrap	7.52	12.5

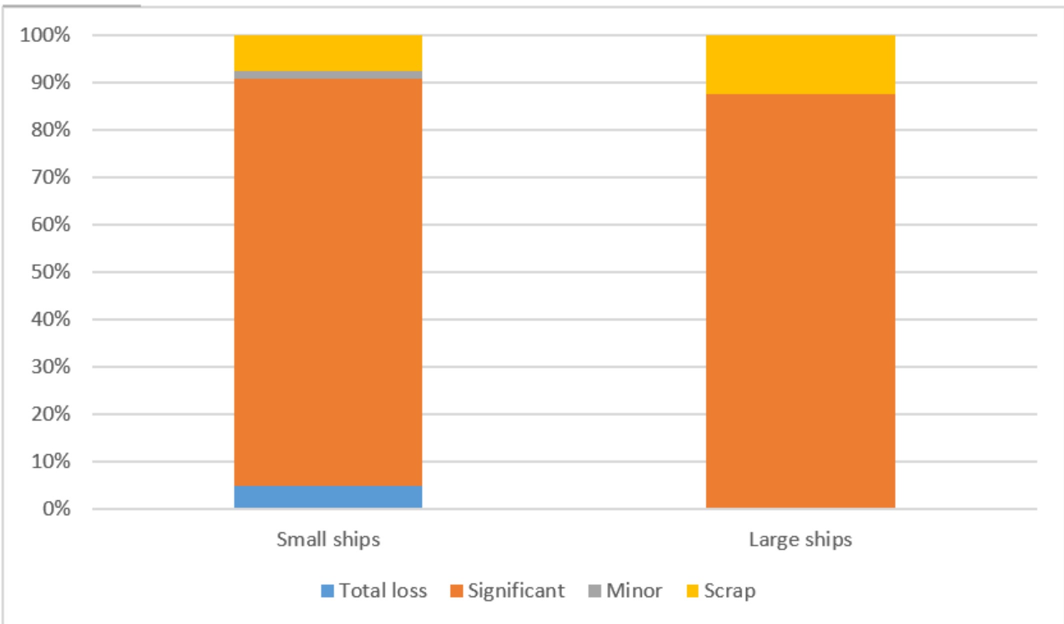


Figure 43: Bar chart based on the data presented in Table 9.

The representation shows that "significant" accidents have the same probability for both small and large vessels. "Scrap" probabilities are also close (7.52% for small ships and 12.5% for large ships). However, "total loss" and "minor" accidents are non-existent in large vessels, while they account for 4.87% and 1.77% respectively for crack accidents in small vessels.

It's worth noting that statistical data gathered for small ships was much greater in number than that collected for large ships (226 versus 80). That means that statistics for small ships are more reliable when compared to those of large vessels.

Cumulative risk comparison

The final decision as to whether an accident is dangerous or not comes from calculating its risk value. Both probability (frequency) and severity are taken into account, thus creating a more reliable index for assessing a hazard.

Table 10: Probabilities, expected values and accumulative risk for fatalities in small and large ships from cracks.

	Small ships			Large ships		
Degree of severity	Fatality probability [%]	Average lives lost [fatalities]	Cumulative risk value [fatalities/ship-life]	Fatality probability [%]	Average lives lost [fatalities]	Cumulative risk value [fatalities/ship-life]
Total loss	12.5	3	0.0166	0	-	-
Significant	75	1.485	0.3843	0	-	-
Minor	0	-	-	0	-	-
Scrap	12.5	1.2	0.0053	100	2.1	0.0263
Grand total	3.54	-	0.4062	1.25	-	0.0263

Table 11: Probabilities, expected values and accumulative risk for oil pollution in small and large ships from cracks.

	Small ships			Large ships		
Degree of severity	Pollution probability [%]	Average oil pollution [tones]	Cumulative risk value [tones/shiplife]	Pollution probability [%]	Average oil pollution [tones]	Cumulative risk value [tones/ship life]
Total loss	64.71	113.64	4.54	0	-	-
Significant	23.53	50	14.16	100	46.67	11.25
Minor	0	-	-	0	-	-
Scrap	11.76	25.21	0.23	0	-	-
Grand total	7.52	-	18.93	3.75	-	11.25

Table 12: Probabilities, expected values and accumulative risk for damage to property in small and large ships from cracks.

	Small ships			Large ships		
Degree of severity	Damage probability [%]	Average cost [million $]	Cumulative risk value [million $/shiplife]	Damage probability [%]	Average cost [million $]	Cumulative risk value [million $/shiplife]
Total loss	4.87	3.87	0.19	0	-	-
Significant	85.84	0.12	0.10	87.5	0.30	0.26
Minor	1.77	-	-	0	-	-
Scrap	7.52	6.13	0.46	12.5	20.59	2.57
Grand total	100	-	0.75	100	-	2.84

Schematically, comparisons for each type of consequence are depicted in the charts below.

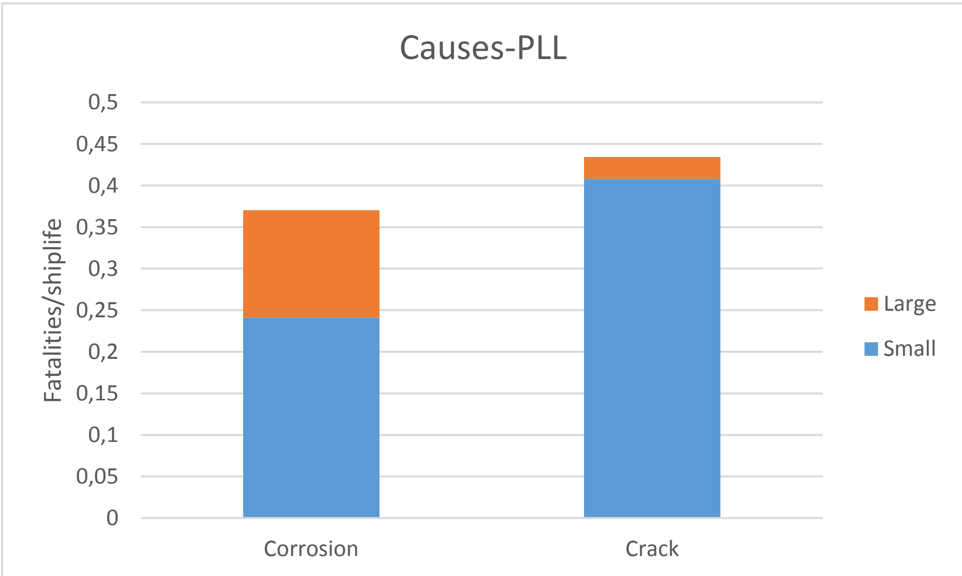


Figure 44: Cumulative risk values for potential loss of life due to corrosion and crack for small and large vessels.

The above chart shows that crack accidents have a higher cumulative PLL. However, although small ships have a higher PLL for crack accidents, large ships have a higher PLL for corrosion-related accidents.

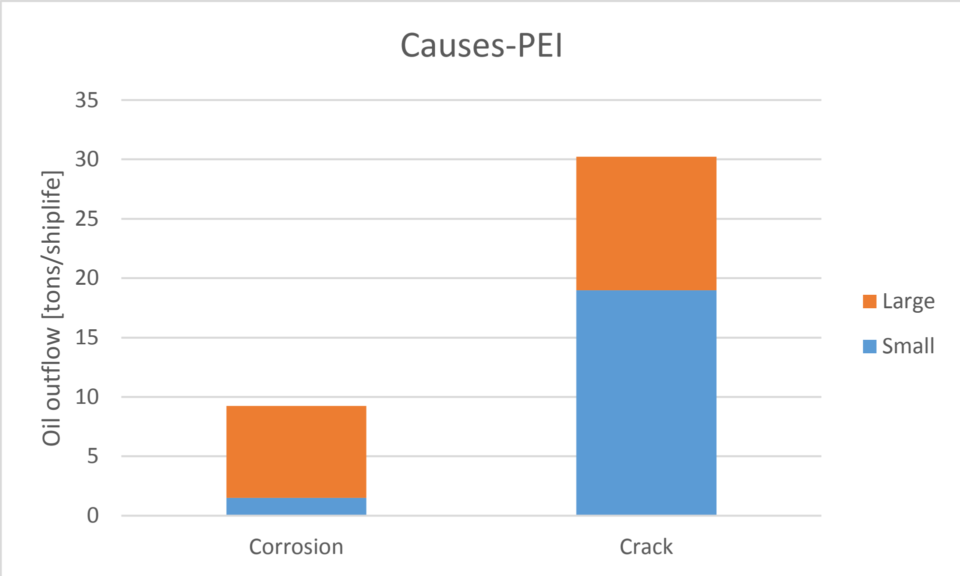


Figure 45: Cumulative risk values for potential environmental impact due to corrosion and crack for small and large vessels.

It can be seen that the risk for oil pollution from corrosion-related accidents is much lower than that for crack accidents. Especially in small vessels, the risk of corrosion-related pollution is extremely small.

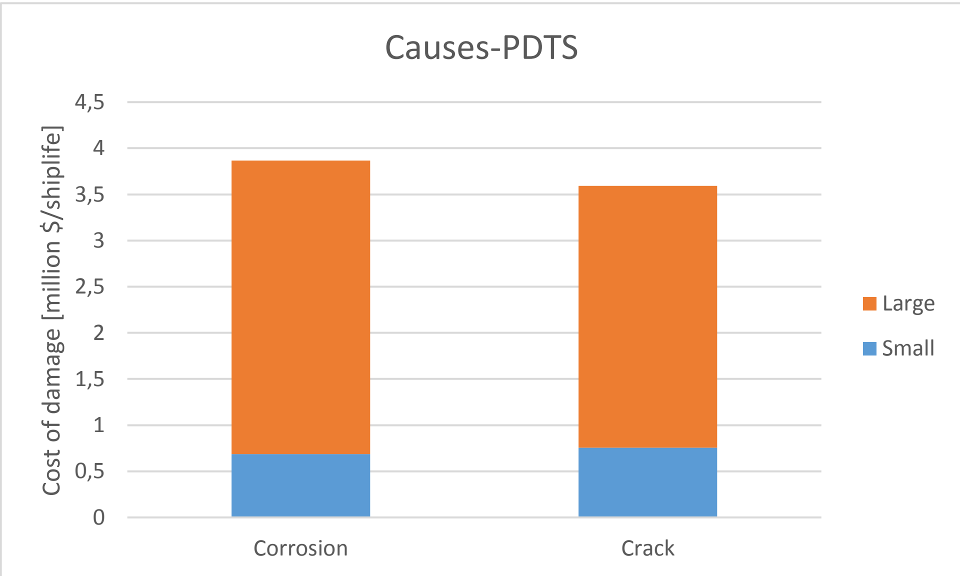


Figure 46: Cumulative risk values for potential damage to property due to corrosion and crack for small and large vessels.

Large ships have a higher PDTS value. This is because repairs are costlier in large vessels in comparison to small ones. Also, PDTS values are almost equal in small ships for both corrosion and crack-related accidents.

9. Conclusions & suggestions for further study

9.1 A critical review on FSA

No single way of work is perfect. In the end, every method is as good as the results it produces. The question whether the FSA approach is better than old reactive regimes can be rephrased as follows: *Does the use of FSA help reduce overall shipping accidents noticeably more than other methods?*

In general, maritime accidents decline steadily every year. As expected, fatalities, pollution from oil spills and damage to property values are reducing too. To say that this is due to the adoption of FSA as a decision-making tool would be an oversimplification.

The FSA approach has flaws as any other method, some of which are critical to neglect. However, it has qualities that make it stand out. These are (Kontovas & Psaraftis, 2009):

- It is proactive

Taking action to mitigate threats before they appear is in any case better than waiting for a casualty to reveal flaws.

- It is systematic

The FSA is comprised of 5 distinct steps. The process followed for each one is carefully structured and leaves little room for deviation.

- It is goal-oriented

Unlike other methods, FSA establishes quantitative risk goals and then examines whether or not these goals are met. If not, different measures are proposed and the risk value is calculated again.

- It is cost-effective

Every measure proposed is assessed in terms of cost effectiveness. From a number of possible solutions, the more efficient in terms of cost is chosen. In this way, the method is friendly to ship owners and other stakeholders who prioritize on monetary return on their investment.

- It incorporates the human factor

It is estimated that roughly 80% of shipping accidents can be attributed to human mistake or negligence. The remaining 20% is due to mechanical issues. Formal Safety Assessment accounts for the human element by utilizing Human Reliability Analysis (HRA) as part of the process. The method identifies room for human error in specific tasks and assigns probabilities to it. Depending on the level of FSA required, Human Resource Analysis can be quantitative or qualitative, or even omitted from the study.

For the above reasons, FSA constitutes a superior method for risk analysis. Nevertheless, some flaws still exist. A careful study performed on the method highlighted the following inadequacies for each of the 5 steps of the process:

Step 1 (HAZID)

- Casualty databases more often than not lack clear information on the cause of an accident, often mistaking consequences as causes and vice versa. The reported sequence of events is also unreliable. As a result data is usually far from accurate and can skew the analysis results.
- Frequency is used interchangeably with probability, although the latter is correct. Although frequency and probability take close numeric values for large data sets, in the case of data scarcity the two numbers can deviate significantly. If, for example, no accident of a certain type is found in the sample, the frequency value for this accident is zero. Probability, however, might be different than zero. There are tools available to account for this issue but till today many FSA reports falsely use frequency instead of risk.
- Despite best efforts, some hazards are left out of the study, simply because they did not come up to the brainstorming session in this step. This poses the obvious danger of leaving a dangerous scenario out of the study.
- The risk matrix used at this step is skewed towards high frequency-low severity accidents, leaving low frequency-catastrophic accidents out of the study. As a result, accidents like Piper Alpha or the Exxon-Valdez disasters can be excluded.
- Whenever expert judgement is required, there always will be a certain level of disagreement amongst them. In cases where discordance is extreme then the course of action taken is not a clarified one. On the contrary, general agreement over a choice indicates that the decision taken is credible.

Step 2 (Risk Analysis)

- When evaluating risk values, both the quality of data used and the methods for their processing these data should be correct. Unfortunately, maritime accident databases present many insufficiencies, as described in Step 1. For example, lack of adequate number of accidents to process, censored reports and privacy surrounding the accidents are major obstacles when performing statistical analysis. Regardless of how sophisticated the method used is, poor data will always generate poor results. As previously stated, lack of proper data is substituted with expert judgement. This allows for a level of subjectivity to enter the calculations.

Step 3 (Risk Control Options – RCO)

- Calculation of risk reduction for each risk control option relies heavily on expert opinion. As a result, the danger of high disagreement can produce unrealistic values and compromise the reliability of the outcome. Furthermore, as is the case in any brainstorming session, some options might be left out of the study.

Step 4 (Cost Benefit Assessment – CBA)

- Measures proposed in FSA can have a tremendous monetary impact on ship owners and other stakeholders in the maritime ecosystem. If an RCO becomes mandatory as part of legislation, significant amounts of money will have to be paid for compliance (retrofitting, training, etc.). As a result -despite best efforts to the contrary- the integrity of the decision committee might become jeopardized. It's essential that "manipulation loopholes" be closed and the process becomes more lucid.
- In benefit assessment, risk control option benefits are only calculated in terms of fatality risk reduction, completely ignoring other factors, such as environmental criteria.

Step 5 (Recommendations for Decision Making)

- Acceptable risk values used for decision-making are arbitrary and are taken from UK Health & Safety Executive (HSE 1999). No exclusive study has been performed to establish tolerable risk values.
- Again, no environmental factors go into the decision process.

Overall, FSA has significantly contributed to the field of risk analysis and has provided practical solutions that help increase maritime safety. However improvements are essential both in the method itself, as well as in the way it is executed.

9.2 Current & future advancements

9.2.1 Goal-Based Standards

Formal Safety Assessment has been in use from 2002 to date and have led to the adoption of significant measures, such as the implementation of double skin bulk carriers. However, the method still presents some flaws, which were presented in the previous passage. In the ever-lasting quest of increasing maritime safety, IMO adopts new methods of dealing with risk. One such method is Goal-Based Standards (abbreviated GBS).

GBS is in force since 2011 and is considered a major milestone in the field of proactive risk analysis. Instead of focusing on specific requirements or specific solutions on ship construction and operation, the method is based on broader goals which should be met. The specific way in which a shipyard/operator chooses to meet these goals are open to individual preference. The following example highlights the way GBS sets rules.

According to traditional maritime legislation regarding the hull's bottom plate thickness of a vessel, current structural rules mandate that the thickness of the plate should be at least X mm. A goal-based approach would instead suggest that the bottom plate should not fail during the ship's life of Y years, operating in a specific environment. If the shipyard provides sound evidence that the chosen plate thickness meets that goal, the legislator is content.

The reasoning behind the creation of GBS is that it eliminates the competition between Classification Societies regarding the quality of construction and opens the door to innovative designs that will remain safe to operate.

The framework of GBS is presented in the chart below.

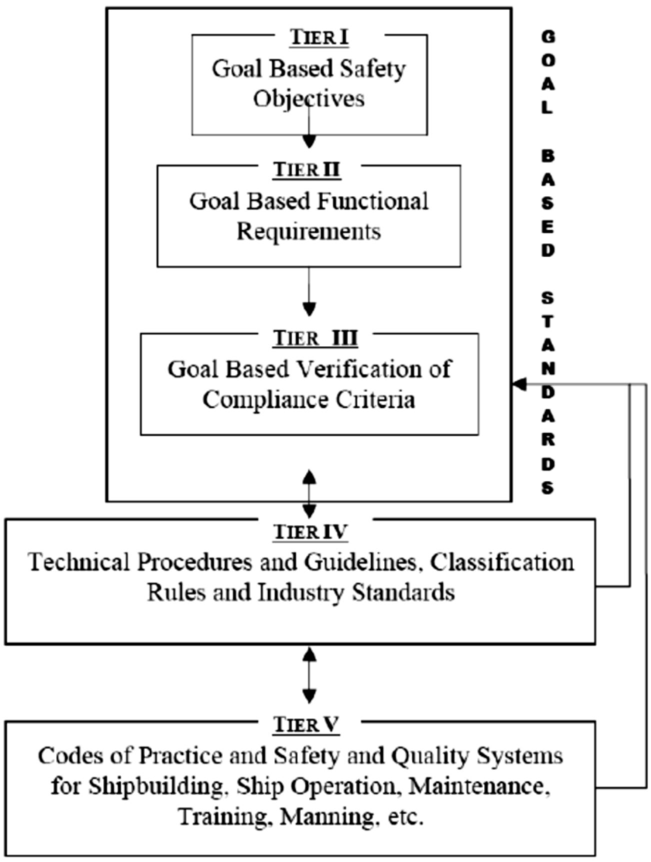


Figure 47: The different stages of GBS safety approach.

9.2.2 Deterministic risk assessment

The calculated risk values can sometimes be misleading, due to inaccuracies in the assessment of both the probability and the severity of the accident. The insufficiencies of PRA can be corrected with the implementation of deterministic risk assessment.

Deterministic safety analysis is used in conjunction with probabilistic analysis and appeals the calculation of the severity for each accident scenario. It makes use of deterministic models based on the principles of engineering to arrive to accurate estimates about the procession of the accident, as well as the severity stemming from it. It differs from statistical modeling, which relies solely on historical data to calculate severity, often leading to extreme divergence from reality.

Deterministic risk assessment is already utilized by the nuclear industry and other high risk sectors.

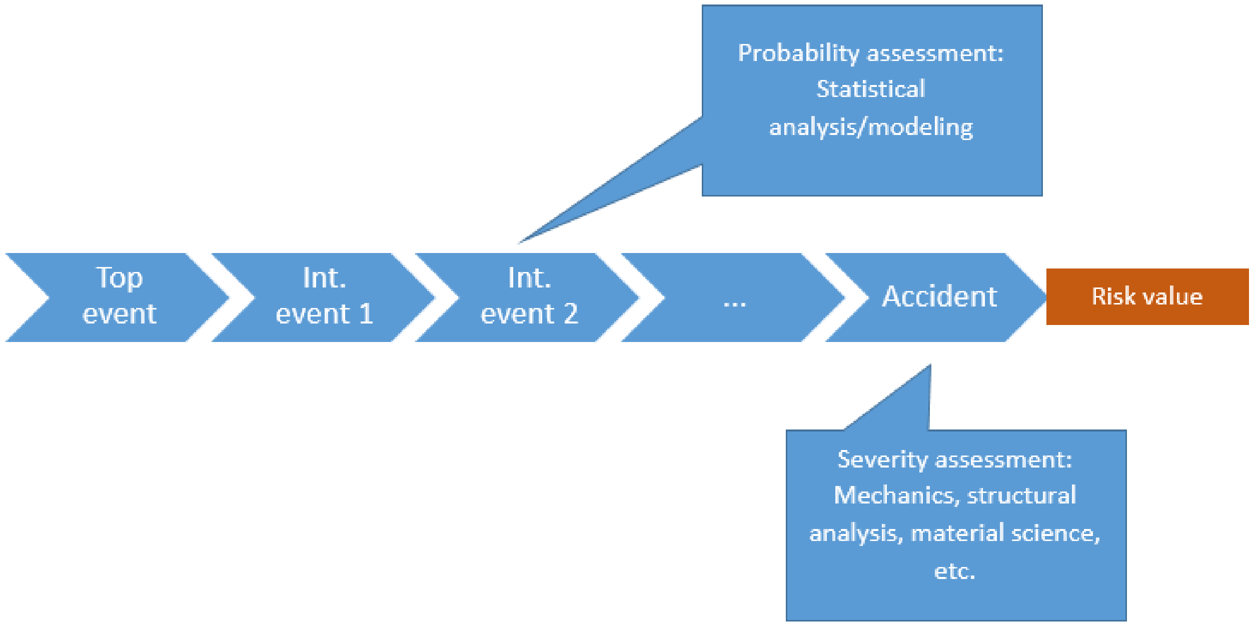


Figure 48: Deterministic analysis is used in conjunction with statistical analysis to increase the accuracy of the final risk value.

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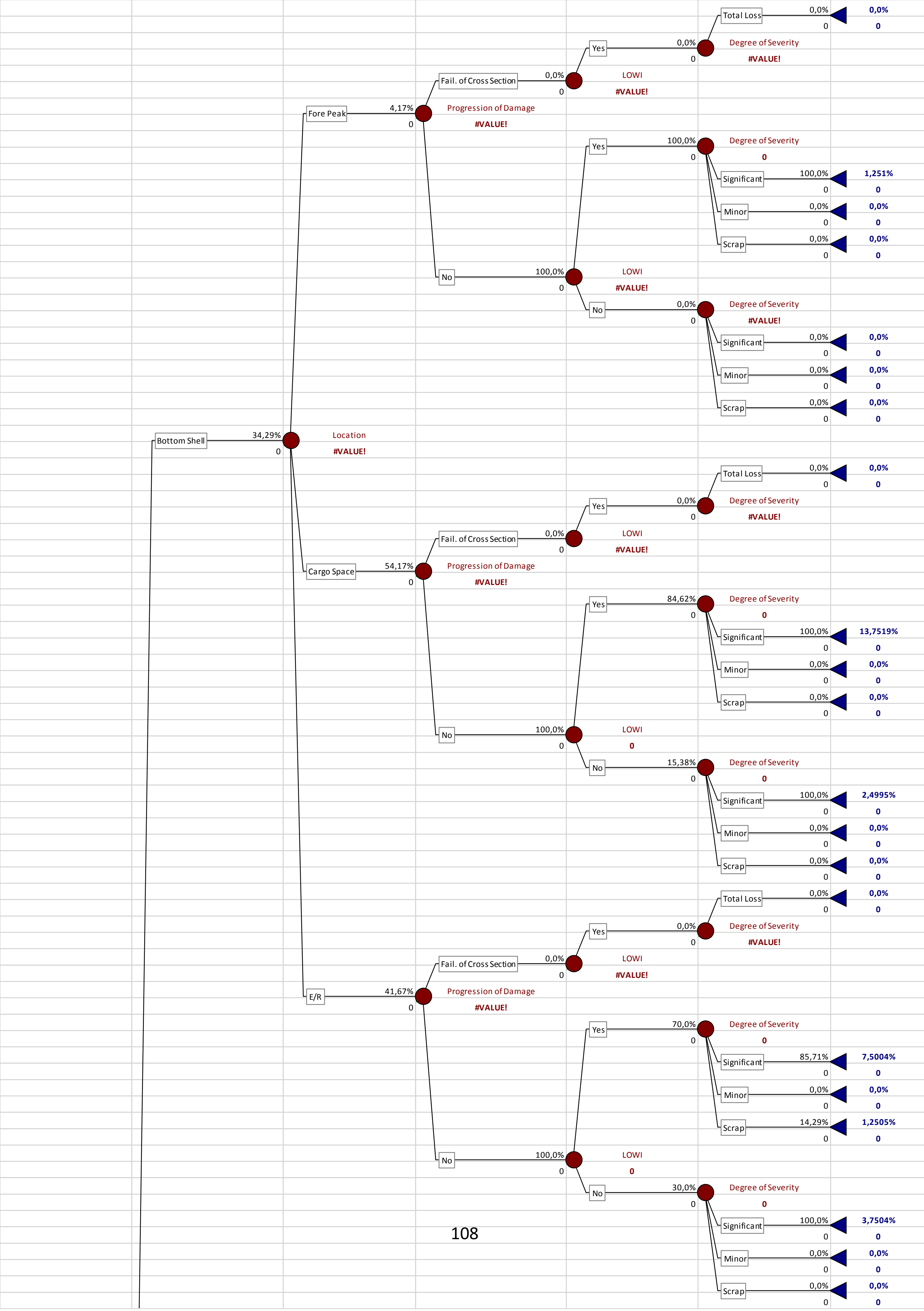
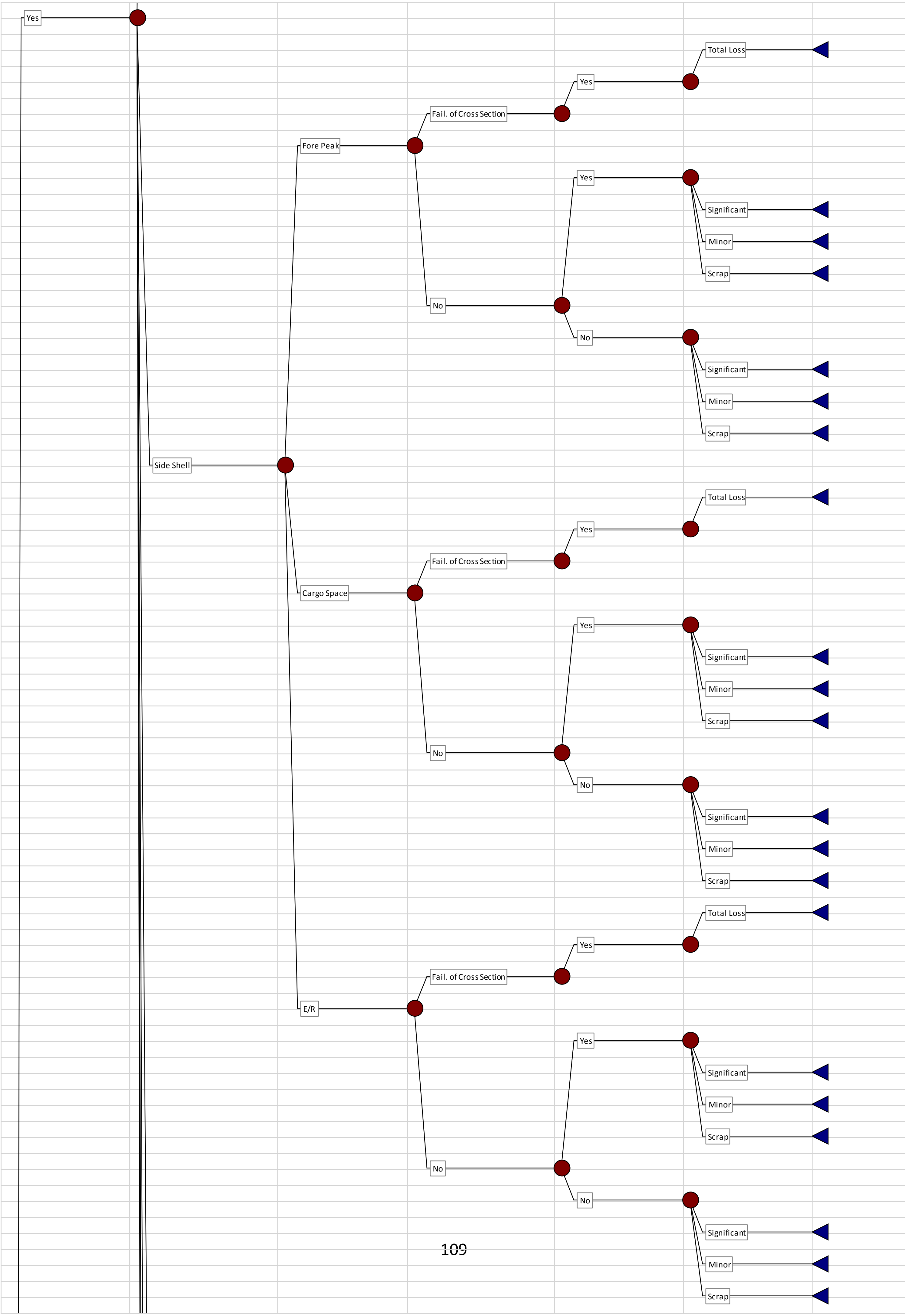
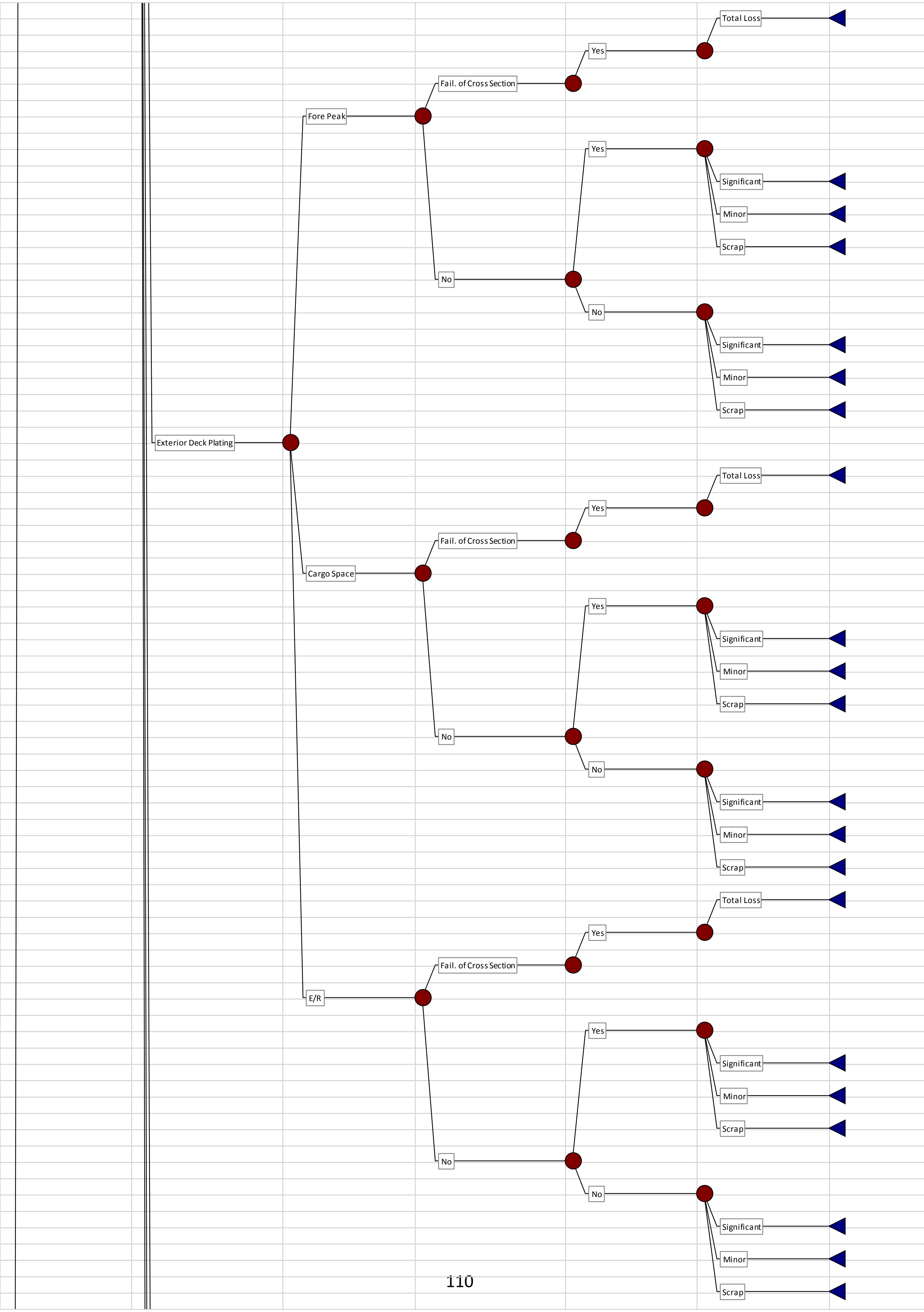
Annex: Event Tree

The following annex encloses the Event Tree used for the evaluation of risk. Due to its large size, it was deemed purposeful to attach it to the end of the document.

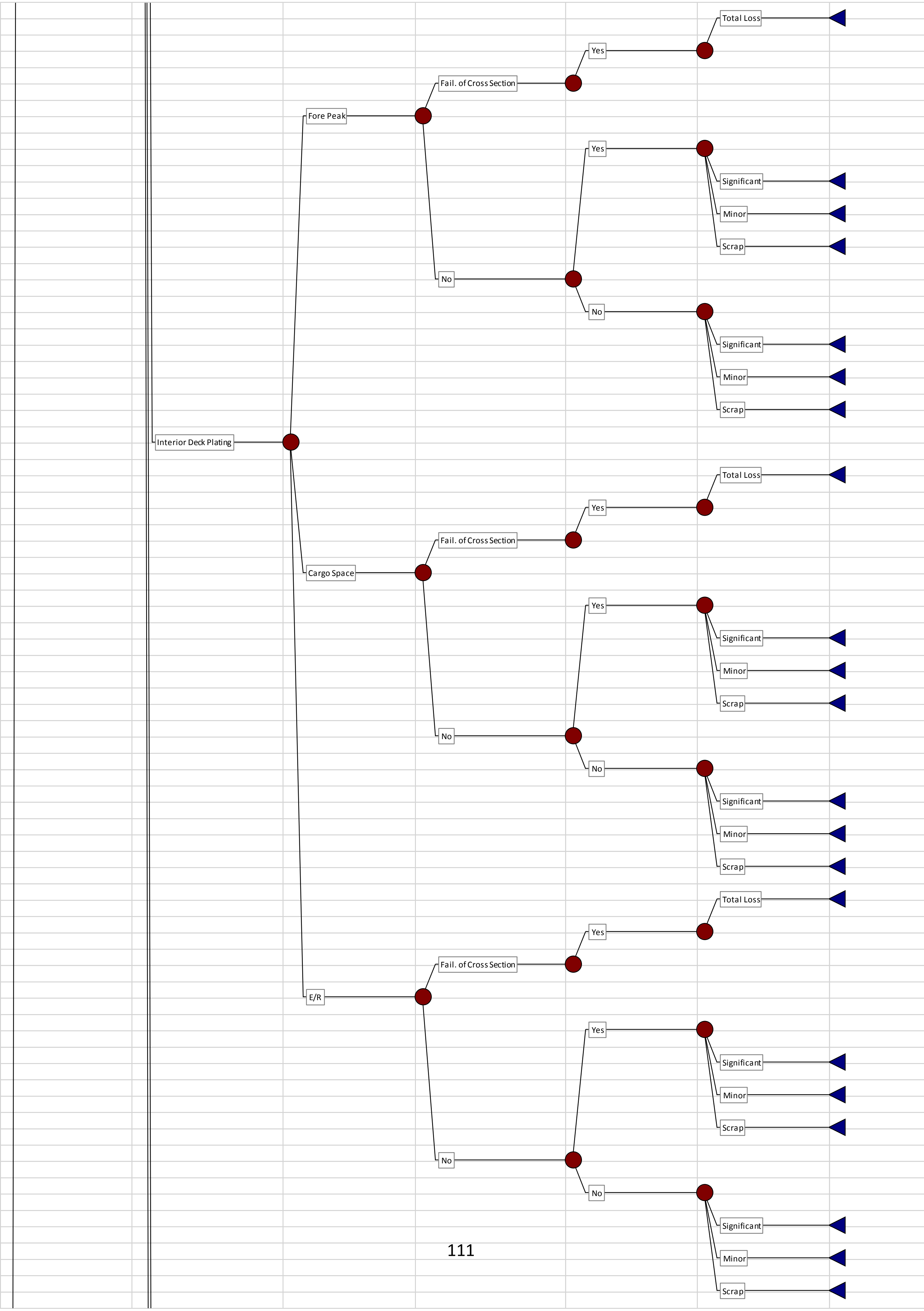
Occurrence in hull	Starting Point	Location	Progression of damage	LOWI	Degree of severity

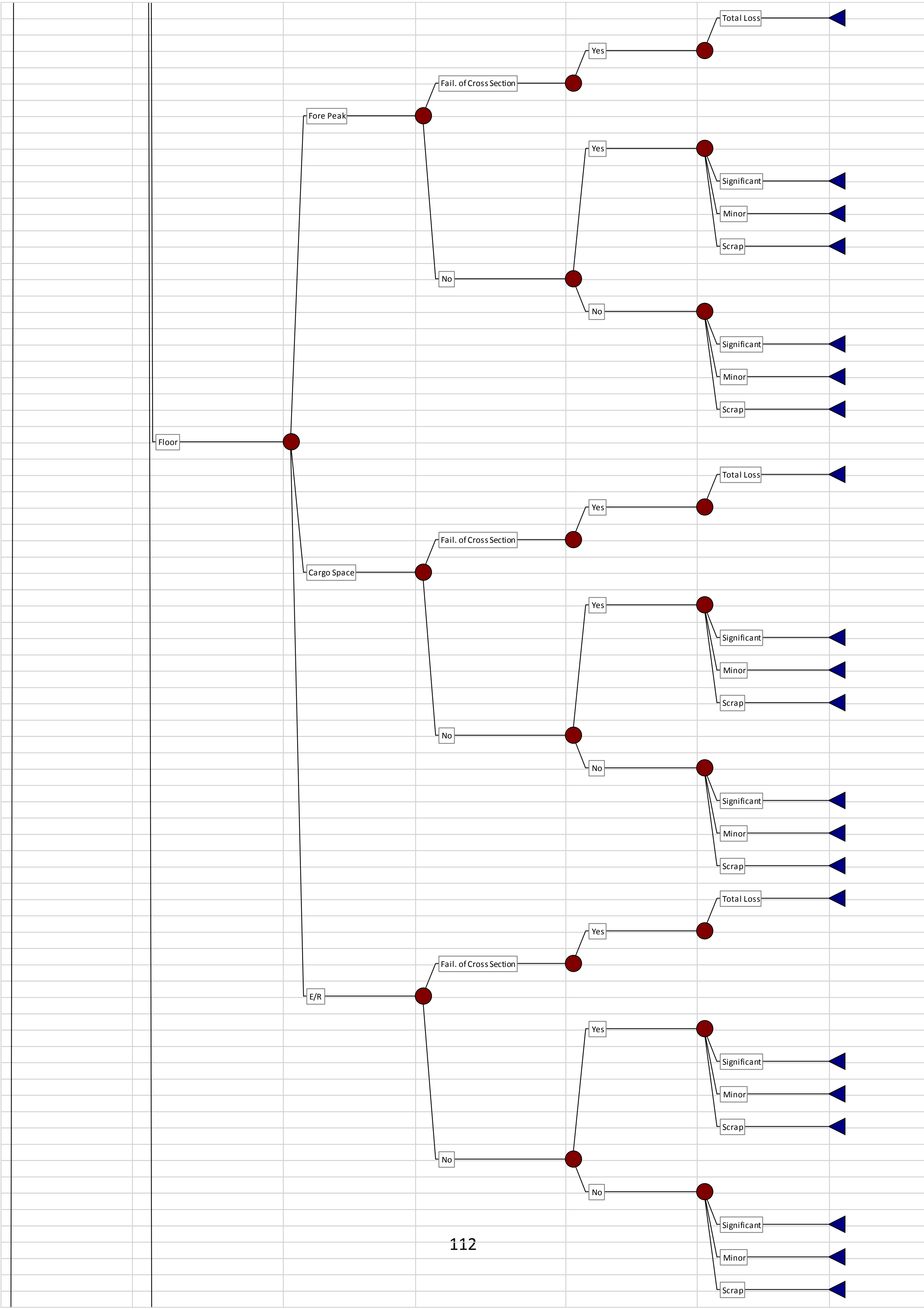



Yes
Side Shell
Fore Peak
Fail. of Cross Section
Yes
Total Loss
No
Yes
Significant
Minor
Scrap
No
Significant
Minor
Scrap
Cargo Space
Fail. of Cross Section
Yes
Total Loss
No
Yes
Significant
Minor
Scrap
No
Significant
Minor
Scrap
E/R
Fail. of Cross Section
Yes
Total Loss
No
Yes
Significant
Minor
Scrap
No
Significant
Minor
Scrap



Exterior Deck Plating
Fore Peak
Cargo Space
E/R
Fail. of Cross Section
Yes
No
Total Loss
Significant
Minor
Scrap


Interior Deck Plating
Fore Peak
Fail. of Cross Section
Yes
Total Loss
Yes
Significant
Minor
Scrap
No
No
Significant
Minor
Scrap
Cargo Space
Fail. of Cross Section
Yes
Total Loss
Yes
Significant
Minor
Scrap
No
No
Significant
Minor
Scrap
E/R
Fail. of Cross Section
Yes
Total Loss
Yes
Significant
Minor
Scrap
No
No
Significant
Minor
Scrap


Floor
Fore Peak
Fail. of Cross Section
Yes
Total Loss
No
Yes
Significant
Minor
Scrap
No
Significant
Minor
Scrap
Cargo Space
Fail. of Cross Section
Yes
Total Loss
No
Yes
Significant
Minor
Scrap
No
Significant
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E/R
Fail. of Cross Section
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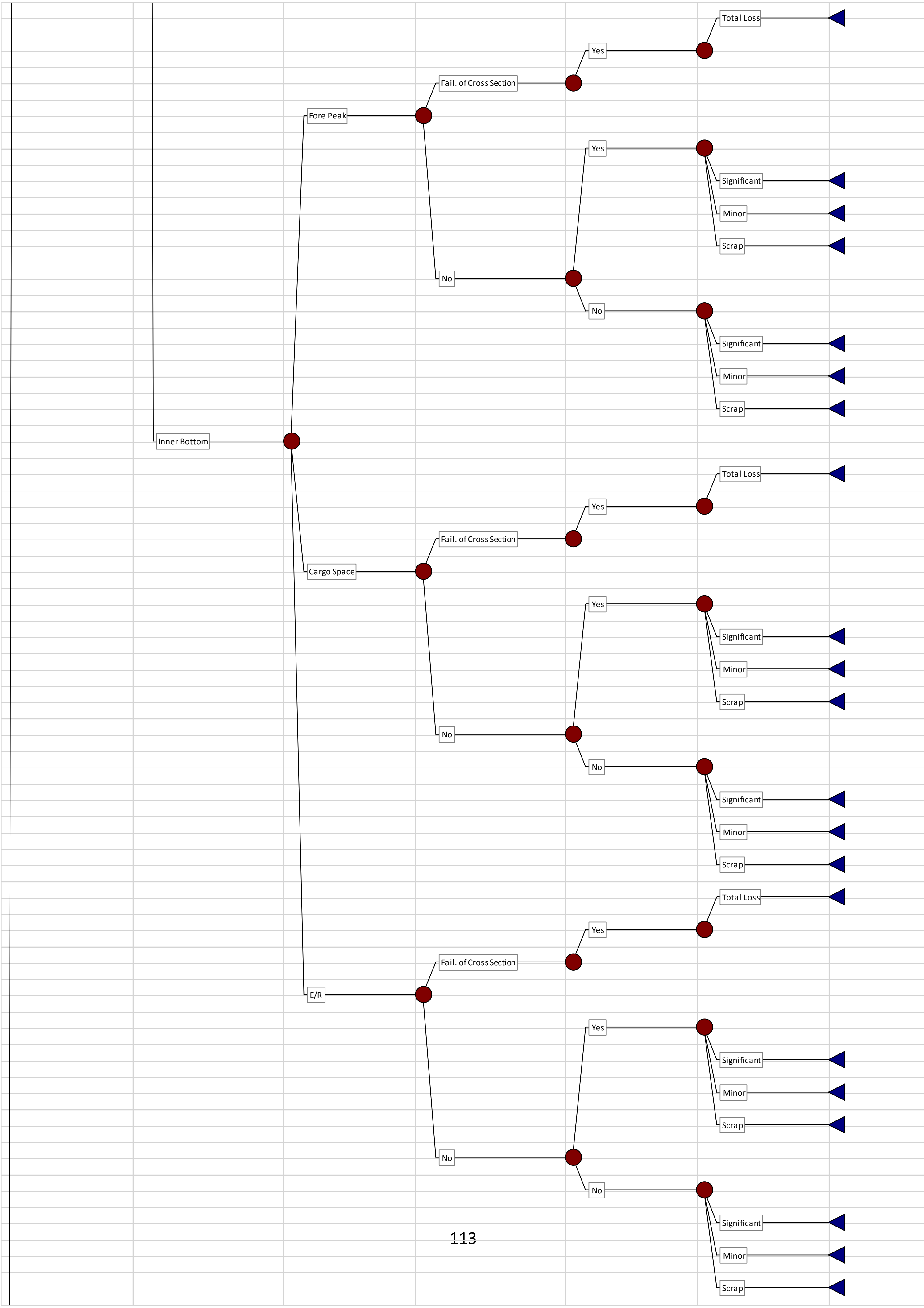
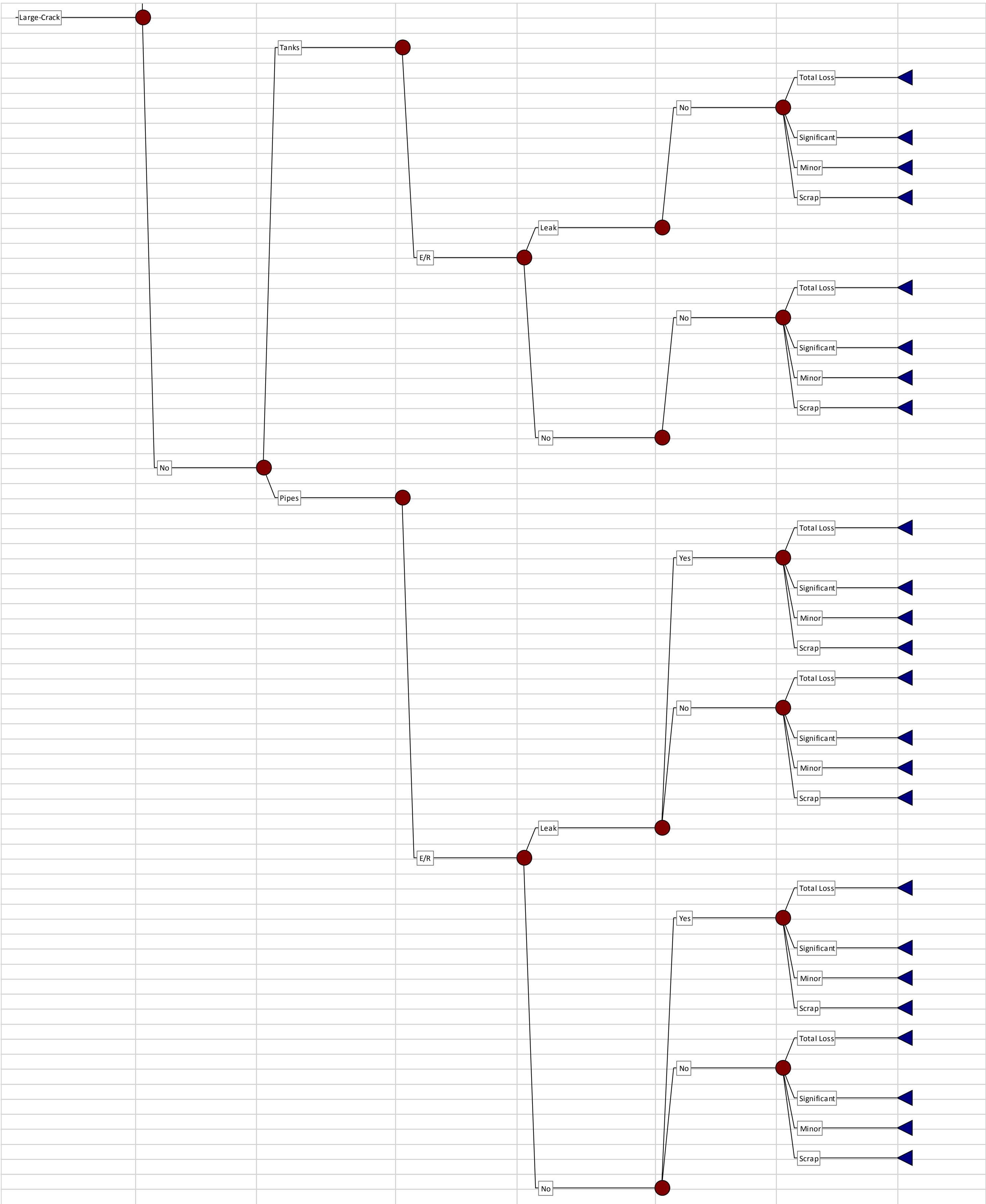
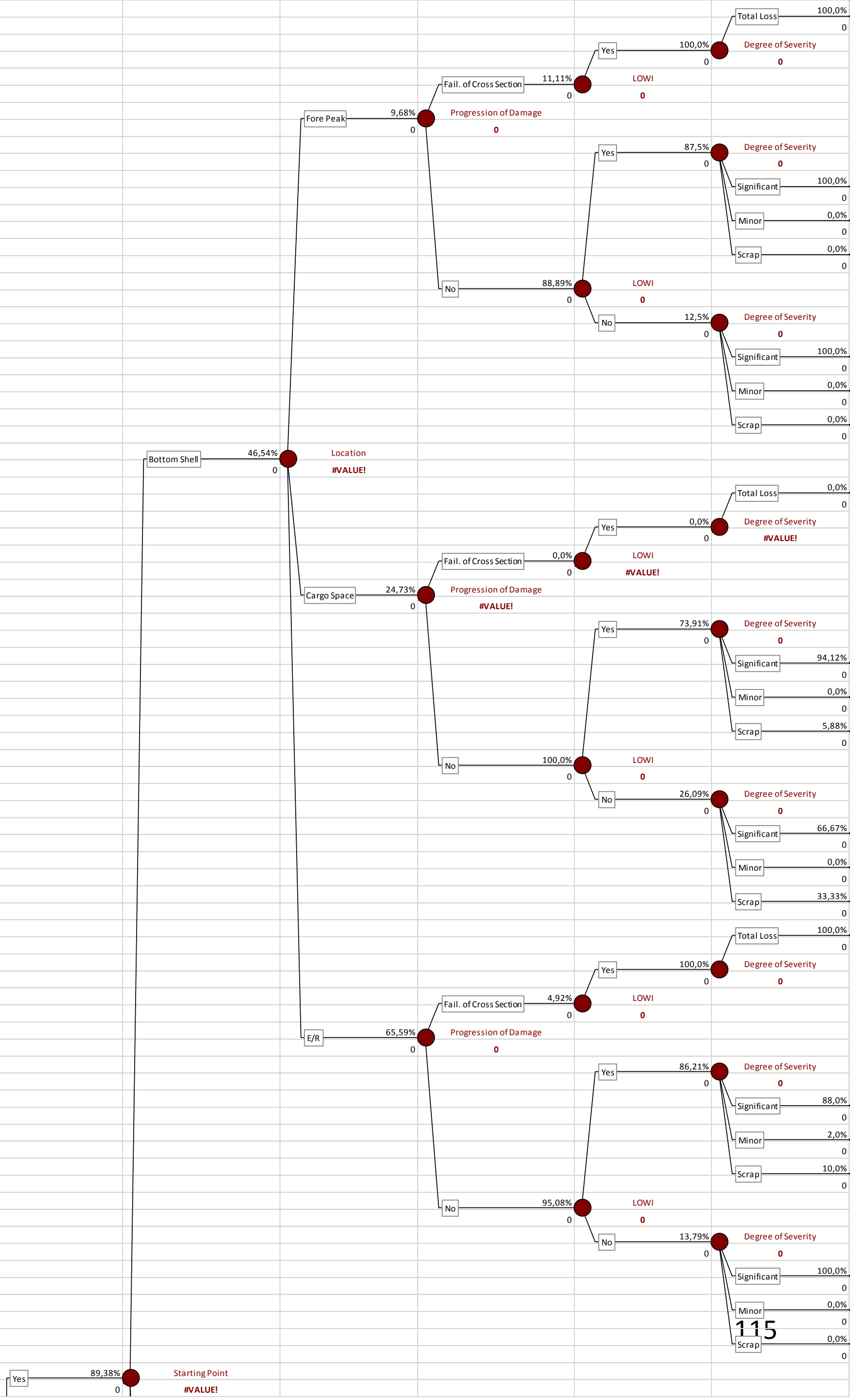
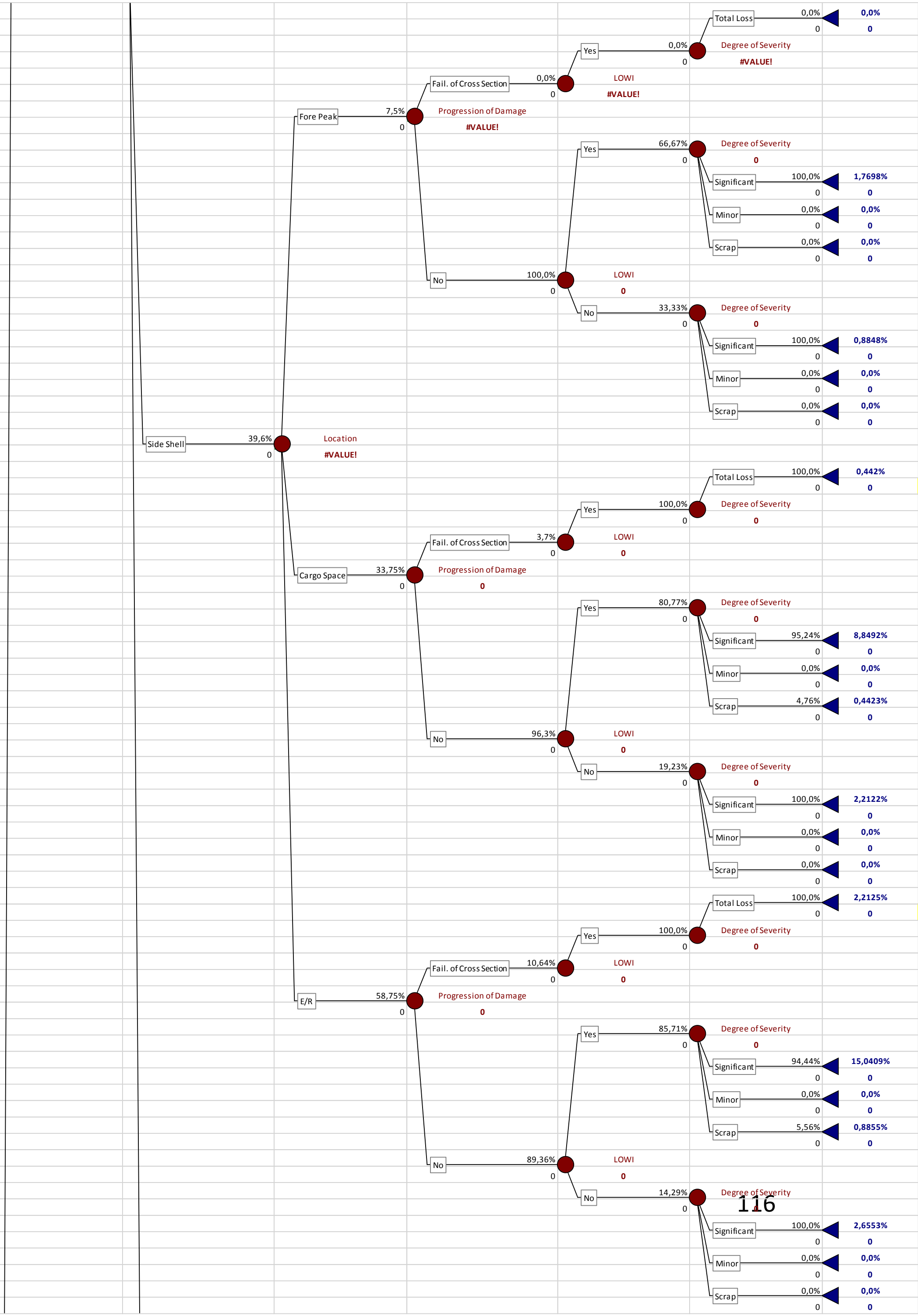
Scrap
No
Significant
Minor
Scrap


Inner Bottom
Fore Peak
Fail. of Cross Section
Yes
Total Loss
Yes
Significant
Minor
Scrap
No
No
Significant
Minor
Scrap
Total Loss
Yes
Fail. of Cross Section
Cargo Space
Yes
Significant
Minor
Scrap
No
No
Significant
Minor
Scrap
Total Loss
Yes
Fail. of Cross Section
E/R
Yes
Significant
Minor
Scrap
No
No
Significant
Minor
Scrap

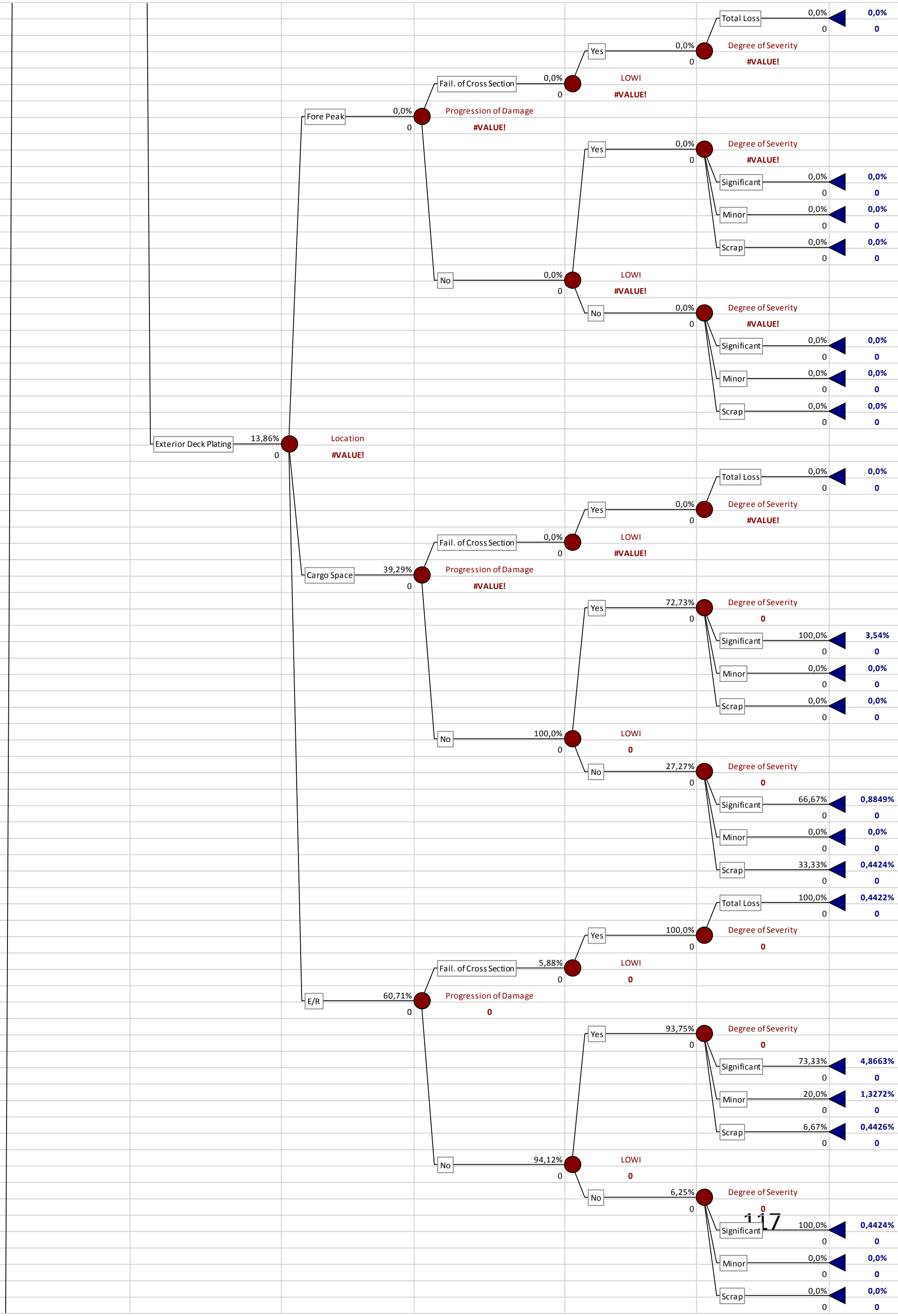

Large-Crack
No
Tanks
Pipes
E/R
Leak
No
Yes
Total Loss
Significant
Minor
Scrap



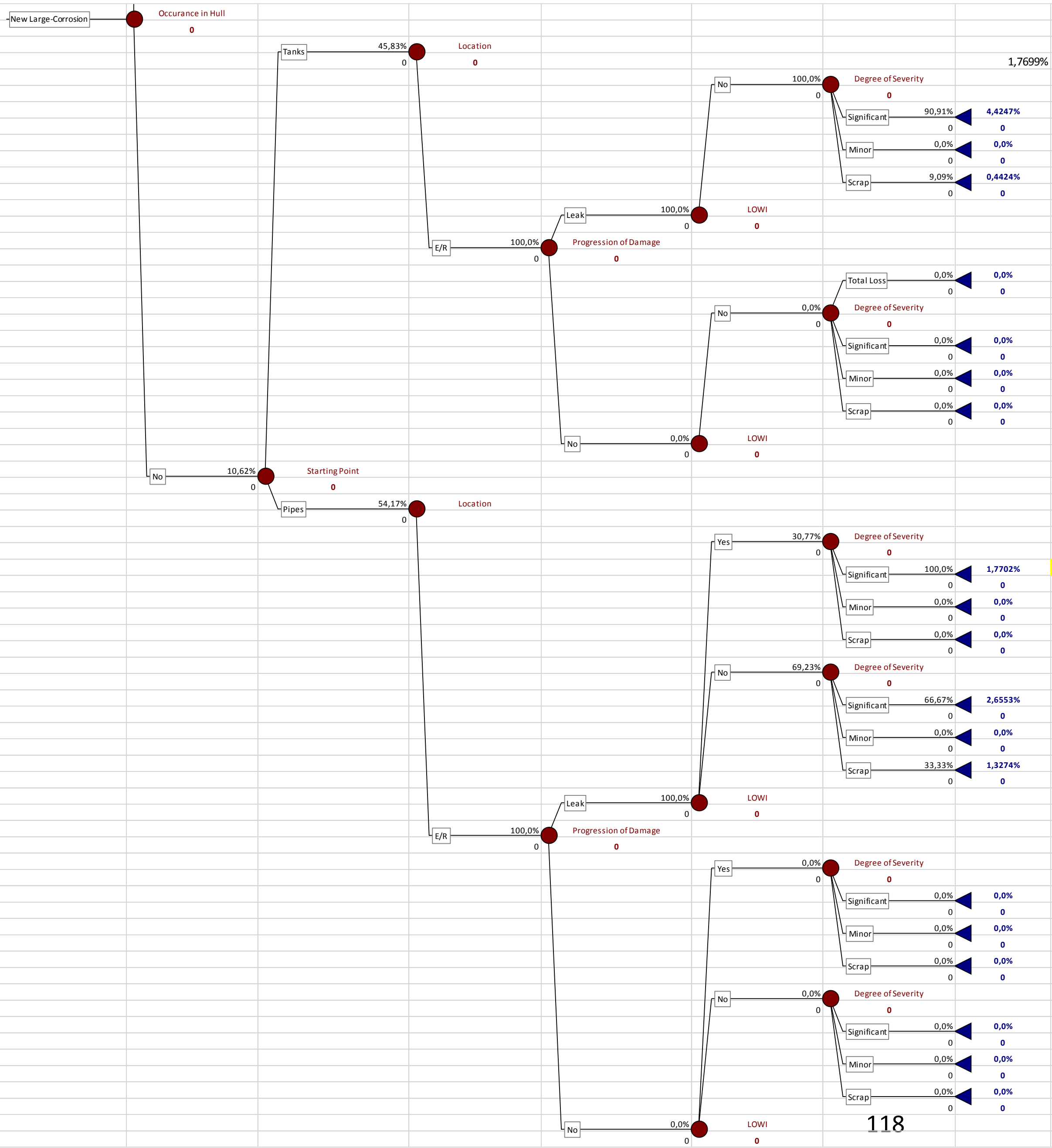
Probability	Fatalities	Environmental Impact	Damage to property	PLL	PEI	PDTS
0,4474%	0	120	2689041	0	0,536830759	12029,666
3,1319%	0,01	0	120000	0,000313187	0	3758,238107
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,4474%	0	0	120000	0	0	536,8911582
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
7,1561%	0	0	120000	0	0	8587,311411
0,0%	0	0	0	0	0	0
0,4471%	0	0,42	6544577	0	0,001877676	29258,56053
1,7894%	0	0	120000	0	0	2147,220407
0,0%	0	0	0	0	0	0
0,8945%	0	0	5229613,4	0	0	46781,03469
1,3424%	0	120	2655016,067	0	1,610833708	35639,91146
19,6804%	0	0	120000	0	0	23616,47616
0,4473%	0	0	0	0	0	0
2,2364%	0	10	4834824,1	0	0,223640873	108126,4281
3,5773%	0	0	120000	0	0	4292,784087
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0



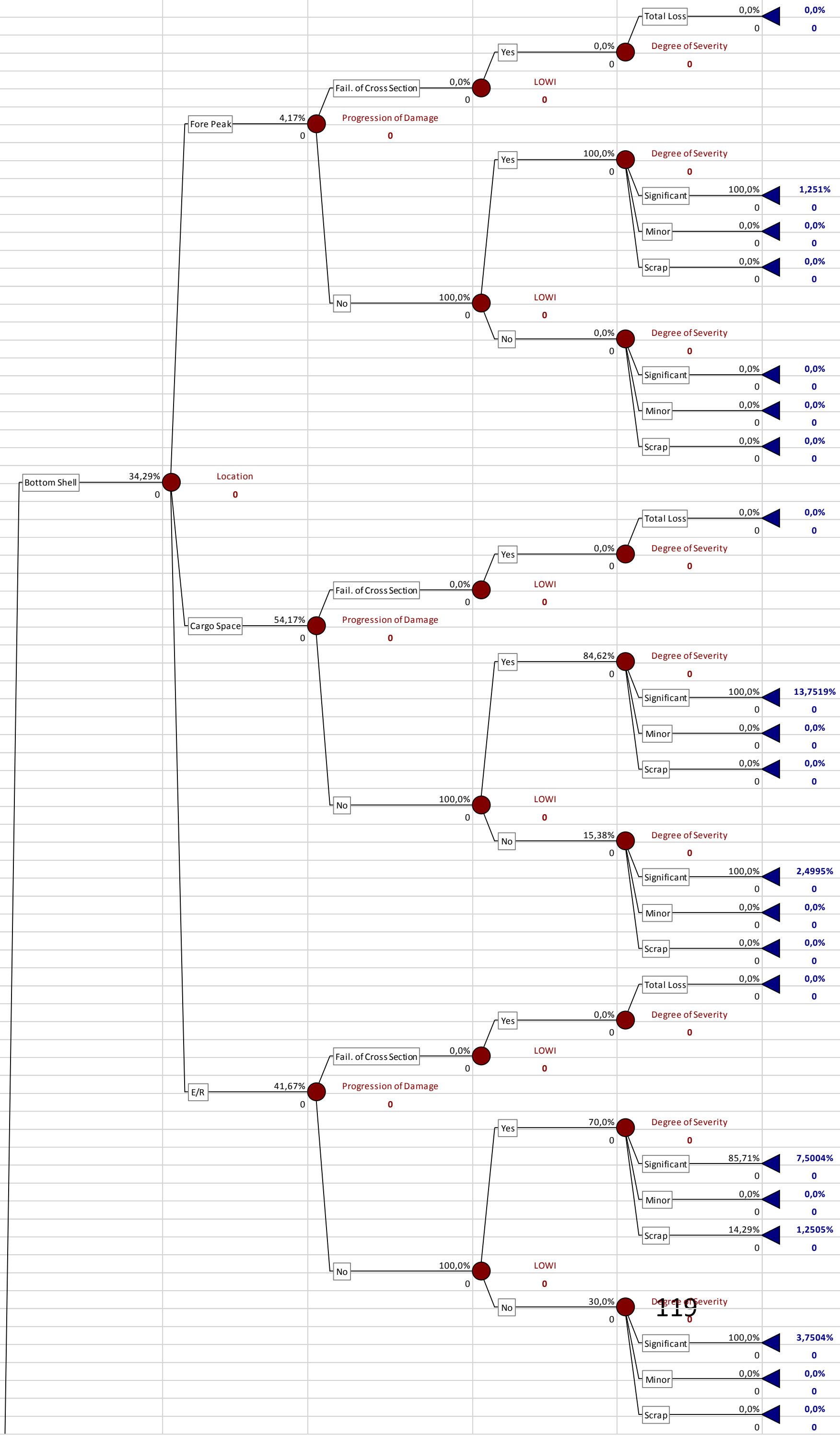
Fore Peak – Total Loss (0,0%)						
Fore Peak – No/Yes – Significant (1,7698%)	0	0	120000	0	0	2123,774983
Fore Peak – No/Yes – Minor (0,0%)	0	0	0	0	0	0
Fore Peak – No/Yes – Scrap (0,0%)	0	0	0	0	0	0
Fore Peak – No/No – Significant (0,8848%)	0	0	120000	0	0	1061,728217
Fore Peak – No/No – Minor (0,0%)	0	0	0	0	0	0
Fore Peak – No/No – Scrap (0,0%)	0	0	0	0	0	0
Cargo Space – Total Loss (0,442%)	0	120	2033060,3	0	0,5304	8986,126526
Cargo Space – No/Yes – Significant (8,8492%)	0	50	120000	0	4,424610794	10619,06591
Cargo Space – No/Yes – Minor (0,0%)	0	0	0	0	0	0
Cargo Space – No/Yes – Scrap (0,4423%)	0	0	9701390,3	0	0	42906,84815
Cargo Space – No/No – Significant (2,2122%)	0	0	120000	0	0	2654,581912
Cargo Space – No/No – Minor (0,0%)	0	0	0	0	0	0
Cargo Space – No/No – Scrap (0,0%)	0	0	0	0	0	0
E/R – Total Loss (2,2125%)	0,75	60	5258548,925	0,016593817	1,327505367	116345,8653
E/R – No/Yes – Significant (15,0409%)	0	50	120000	0	7,520453757	18049,08902
E/R – No/Yes – Minor (0,0%)	0	0	0	0	0	0
E/R – No/Yes – Scrap (0,8855%)	0,6	0	7306385,25	0,005313052	0	64698,68026
E/R – No/No – Significant (2,6553%)	0,2	0	120000	0,005310664	0	3186,398157
E/R – No/No – Minor (0,0%)	0	0	0	0	0	0
E/R – No/No – Scrap (0,0%)	0	0	0	0	0	0



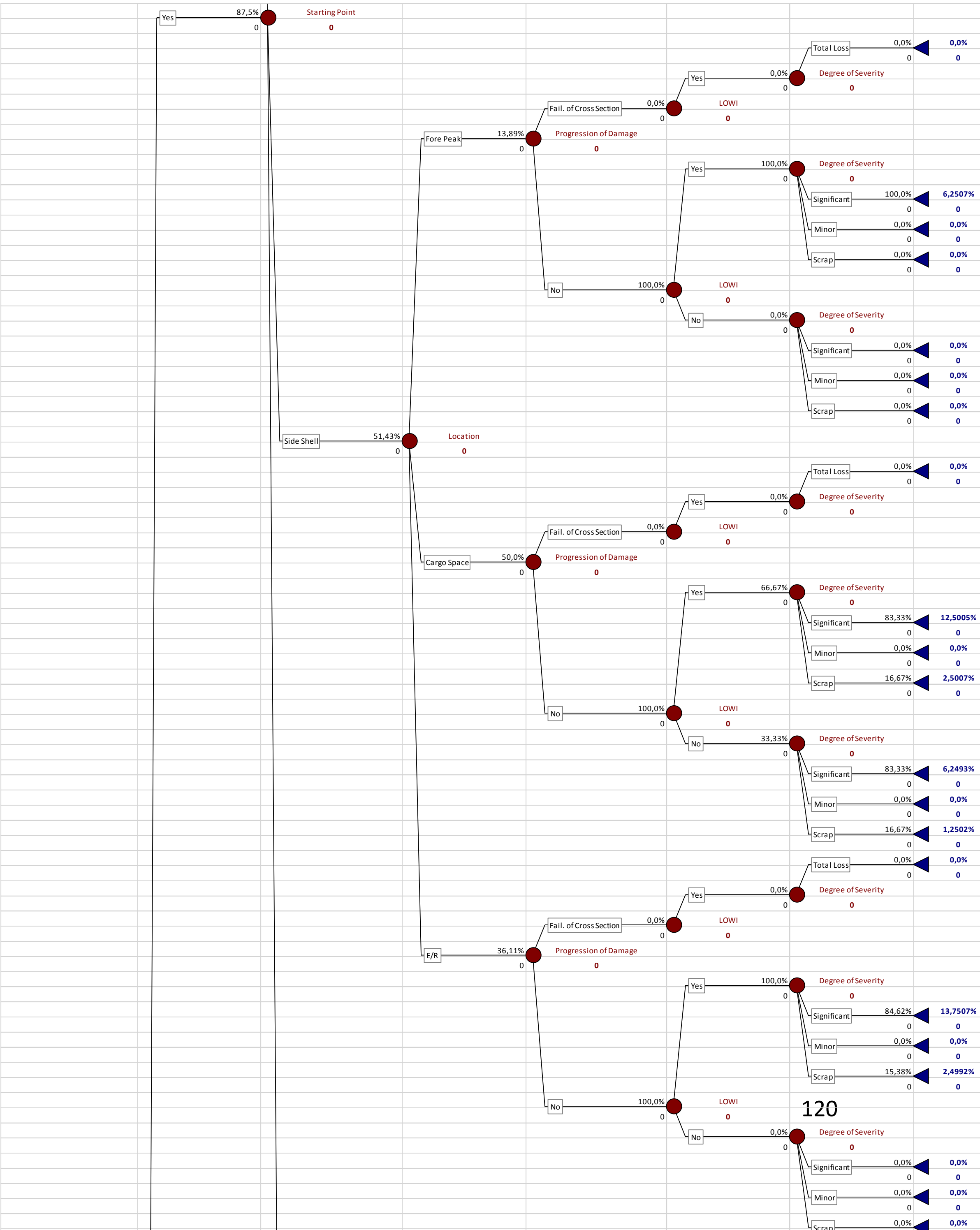
Total Loss	0	0	0	0	0	0
Significant	0	0	120000	0	0	0
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0
Significant	0	0	120000	0	0	0
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0
Total Loss	0	0	0	0	0	0
Significant	0	0	120000	0	0	4247,960238
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0
Significant	0	0	120000	0	0	1061,897134
Minor	0	0	0	0	0	0
Scrap	0	0	4905375,8	0	0	21700,92996
Total Loss	0	120	3613718,6	0	0,53064	15979,86365
Significant	7	0	120000	0,340640854	0	5839,557504
Minor	0	0	0	0	0	0
Scrap	0	0	6097249,2	0	0	26988,37821
Significant	0,1	0	120000	0,000442411	0	530,8929955
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0



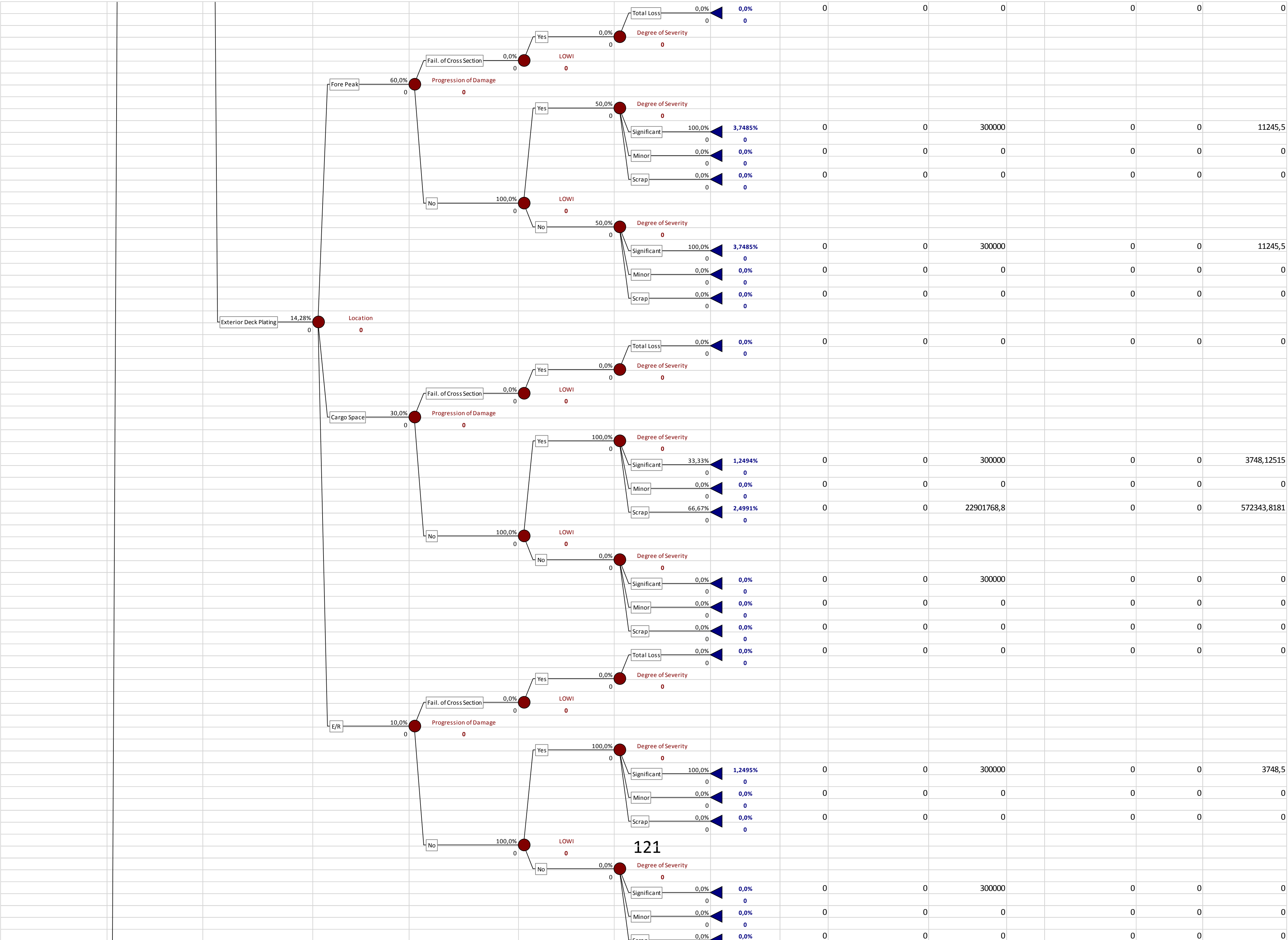
0,55	50	120000	0,024335973	2,212361214	5309,666914
0	0	0	0	0	0
0	0	5505815,8	0	0	24359,0269
0	0	0	0	0	0
0	0	120000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	120000	0	0	2124,24
0	0	0	0	0	0
0	0	0	0	0	0
0,5	0	120000	0,013276333	0	3186,319967
0	0	0	0	0	0
0	0	7375686,033	0	0	97907,37776
0	0	120000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	120000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
			0,4062	18,9192	754642,7918

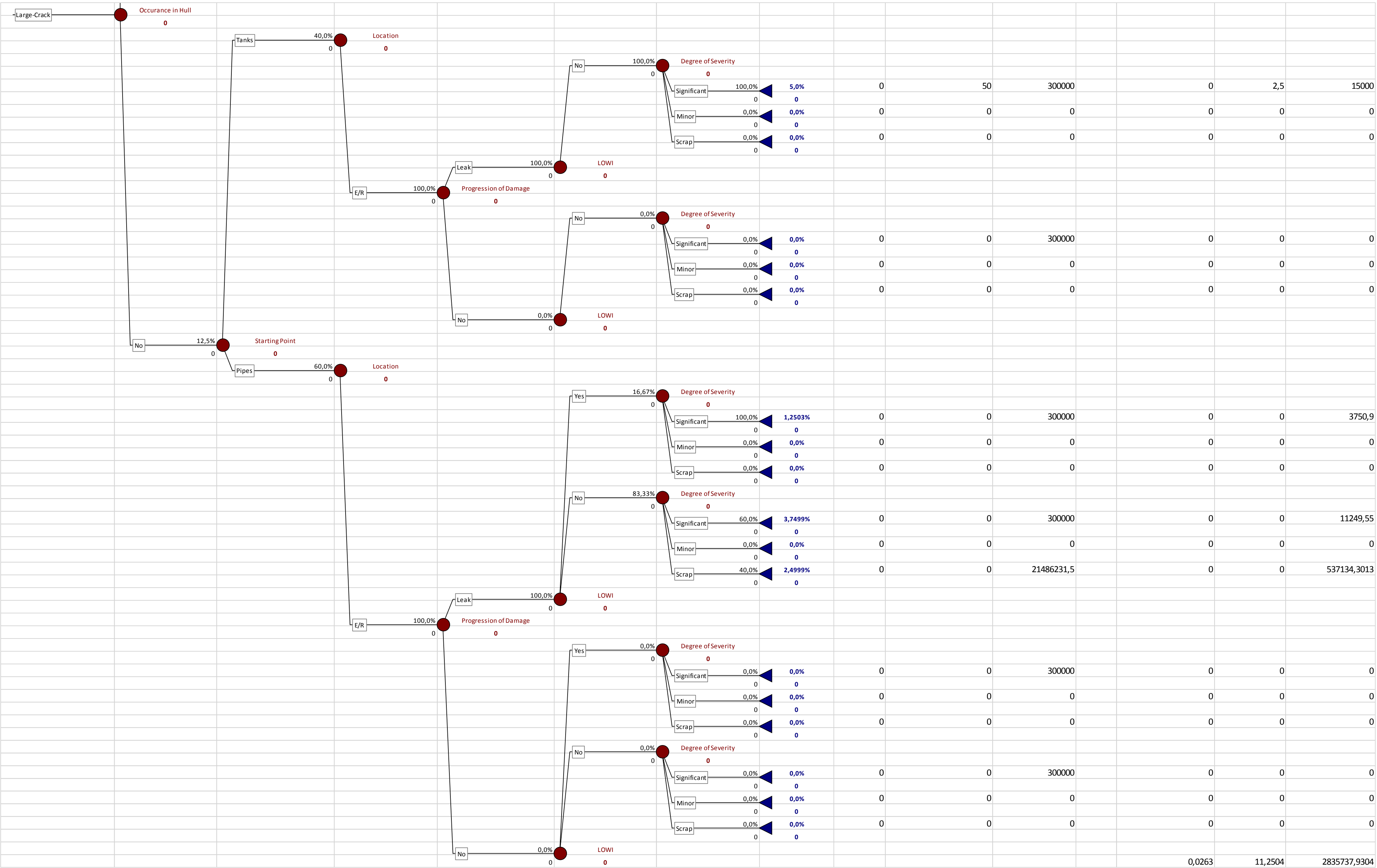


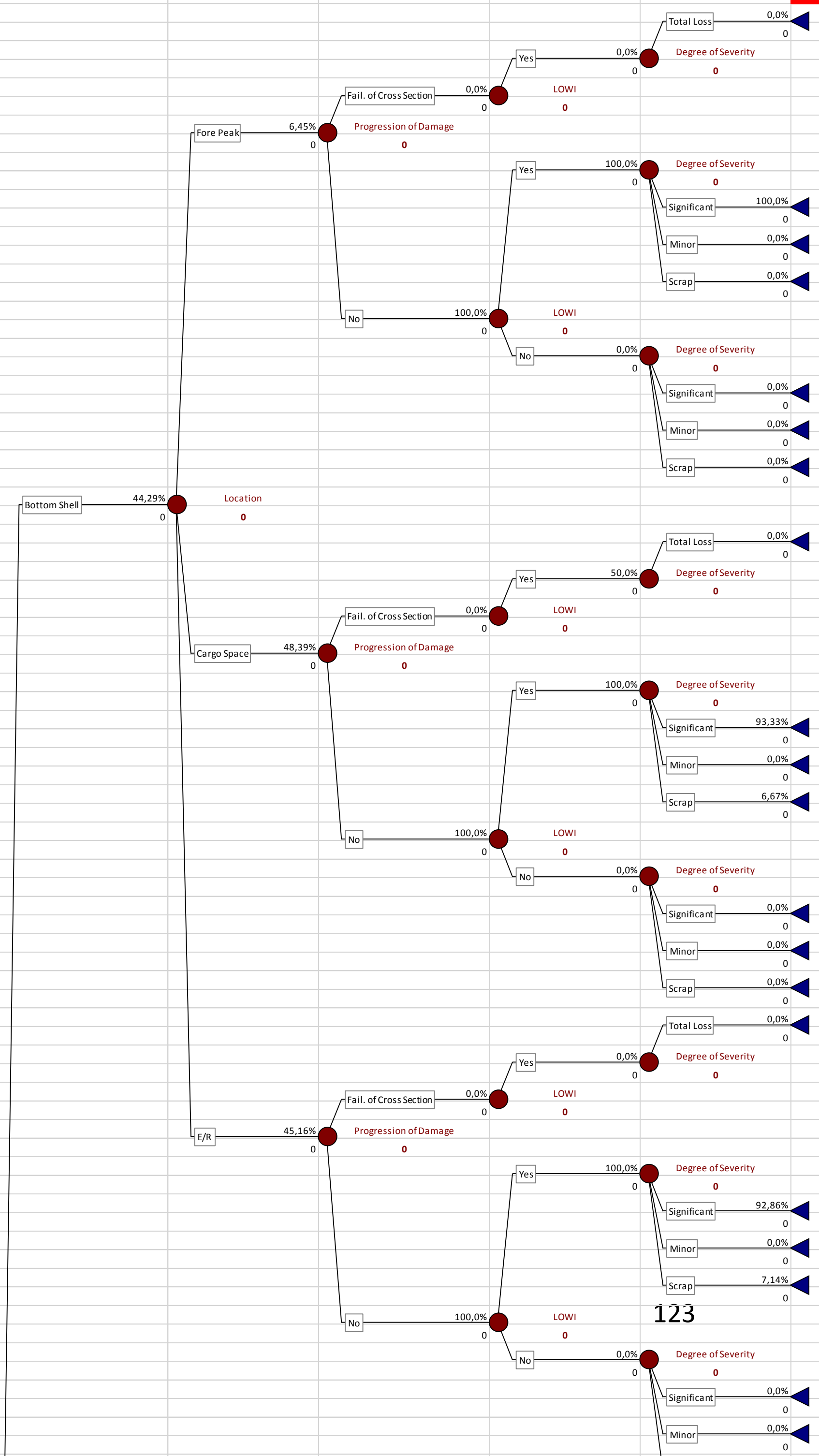
Probability	Fatalities	Environmental Impact	Damage to property	PLL	PEI	PDTS
0,0%	0	0	0	0	0	0
1,251%	0	0	300000	0	0	3753,093816
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	300000	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
13,7519%	0	0	300000	0	0	41255,81987
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
2,4995%	0	0	300000	0	0	7498,398837
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
7,5004%	0	50	300000	0	3,750206228	22501,23737
0,0%	0	0	0	0	0	0
1,2505%	2,1	0	10288025,5	0,026260632	0	128652,4059
3,7504%	0	0	300000	0	0	11251,18124
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0



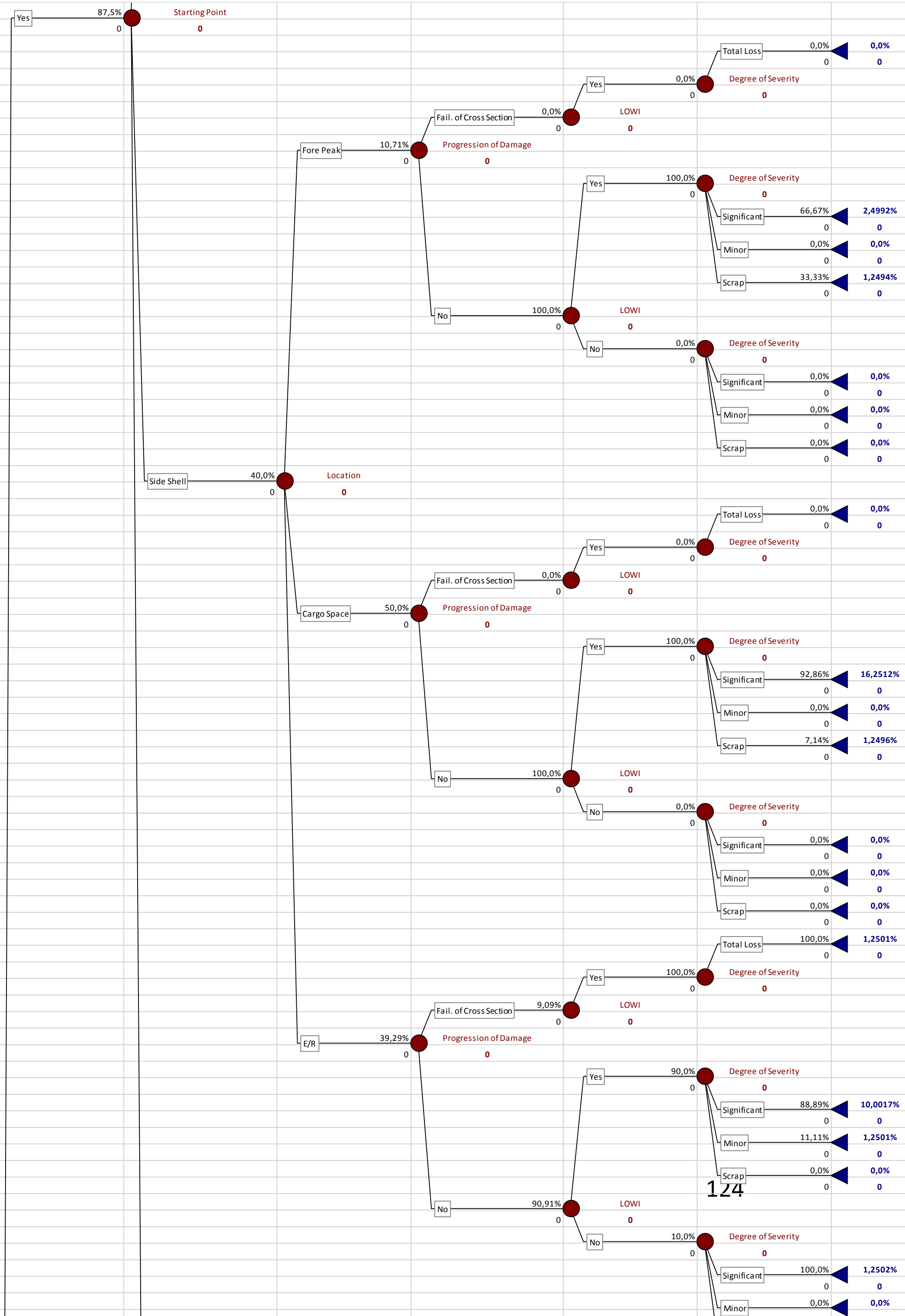
0	0	0	0	0	0
0	0	300000	0	0	18752,02088
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	40	300000	0	5,00018888	37501,4166
0	0	0	0	0	0
0	0	24646797,55	0	0	616341,1075
0	0	300000	0	0	18747,89584
0	0	0	0	0	0
0	0	12823383,4	0	0	160312,7715
0	0	0	0	0	0
0	0	300000	0	0	41252,12656
0	0	0	0	0	0
0	0	22344860,7	0	0	558452,26
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0


Exterior Deck Plating
14,28%
0
Location
0
Fore Peak
60,0%
Progression of Damage
Fail. of Cross Section
0,0%
LOWI
Yes
Degree of Severity
Total Loss
0,0%
No
100,0%
50,0%
Significant
100,0%
3,7485%
Minor
Scrap
Cargo Space
30,0%
33,33%
1,2494%
66,67%
2,4991%
E/R
10,0%
1,2495%
300000
11245,5
3748,12515
22901768,8
572343,8181
3748,5

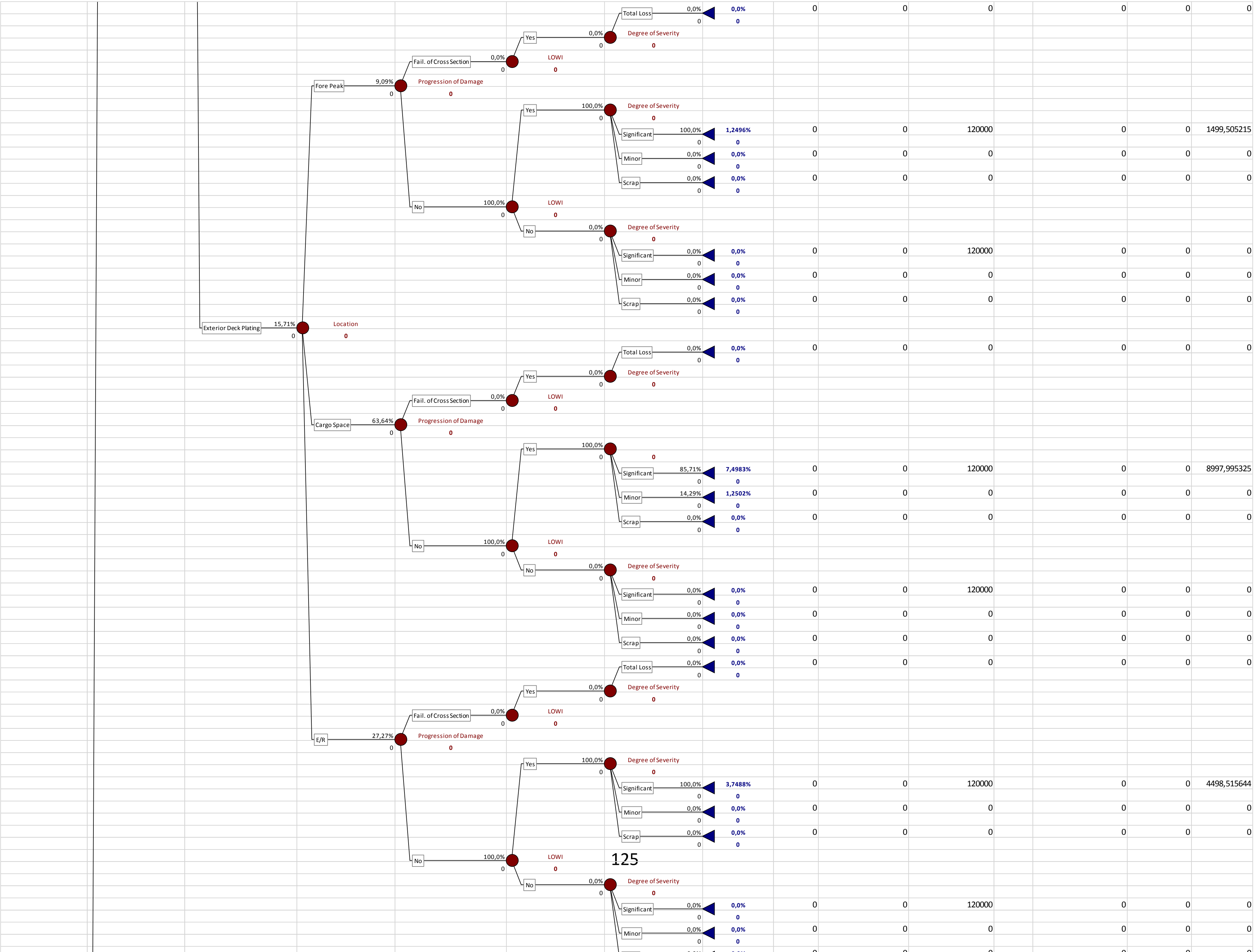

Large-Crack
Occurance in Hull
0
Tanks
40,0%
0
Location
0
No
100,0%
0
Degree of Severity
0
Significant
100,0%
0
5,0%
0
0 50 300000 0 2,5 15000
Minor
0,0%
0
0,0%
0
0 0 0 0 0 0
Scrap
0,0%
0
0,0%
0
0 0 0 0 0 0
Leak
100,0%
0
LOWI
0
E/R
100,0%
0
Progression of Damage
0
No
0,0%
0
Degree of Severity
0
Significant
0,0%
0
0,0%
0
0 0 300000 0 0 0
Minor
0,0%
0
0,0%
0
0 0 0 0 0 0
Scrap
0,0%
0
0,0%
0
0 0 0 0 0 0
No
0,0%
0
LOWI
0
No
12,5%
0
Starting Point
0
Pipes
60,0%
0
Location
0
Yes
16,67%
0
Degree of Severity
0
Significant
100,0%
0
1,2503%
0
0 0 300000 0 0 3750,9
Minor
0,0%
0
0,0%
0
0 0 0 0 0 0
Scrap
0,0%
0
0,0%
0
0 0 0 0 0 0
No
83,33%
0
Degree of Severity
0
Significant
60,0%
0
3,7499%
0
0 0 300000 0 0 11249,55
Minor
0,0%
0
0,0%
0
0 0 0 0 0 0
Scrap
40,0%
0
2,4999%
0
0 0 21486231,5 0 0 537134,3013
Leak
100,0%
0
LOWI
0
E/R
100,0%
0
Progression of Damage
0
Yes
0,0%
0
Degree of Severity
0
Significant
0,0%
0
0,0%
0
0 0 300000 0 0 0
Minor
0,0%
0
0,0%
0
0 0 0 0 0 0
Scrap
0,0%
0
0,0%
0
0 0 0 0 0 0
No
0,0%
0
Degree of Severity
0
Significant
0,0%
0
0,0%
0
0 0 300000 0 0 0
Minor
0,0%
0
0,0%
0
0 0 0 0 0 0
Scrap
0,0%
0
0,0%
0
0 0 0 0 0 0
No
0,0%
0
LOWI
0
0,0263 11,2504 2835737,9304

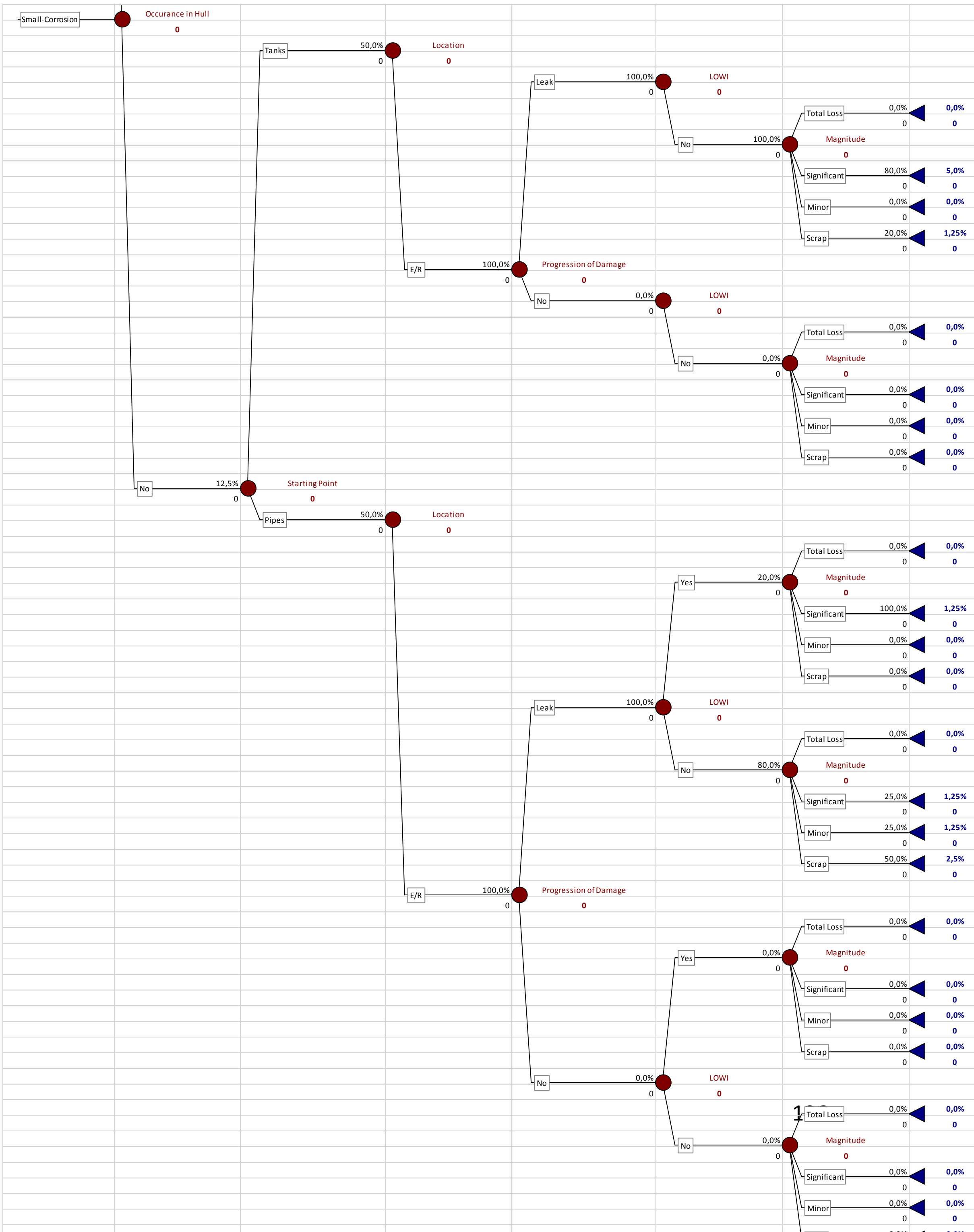


Probability	Fatalities	Environmental Impact	Damage to property	PLL	PEI	PDTS
0,0%	0	0	0	0	0	0
2,5%	0	0	120000	0	0	3000,041479
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	120000	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
17,5007%	0	0	120000	0	0	21000,80031
0,0%	0	0	0	0	0	0
1,2507%	0	0	5992172,2	0	0	74945,13615
0,0%	0	0	120000	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
16,2507%	0	0	120000	0	0	19500,86962
0,0%	0	0	0	0	0	0
1,2495%	0	0	10025627,9	0	0	125271,9526
0,0%	0	0	120000	0	0	0
0,0%	0	0	0	0	0	0

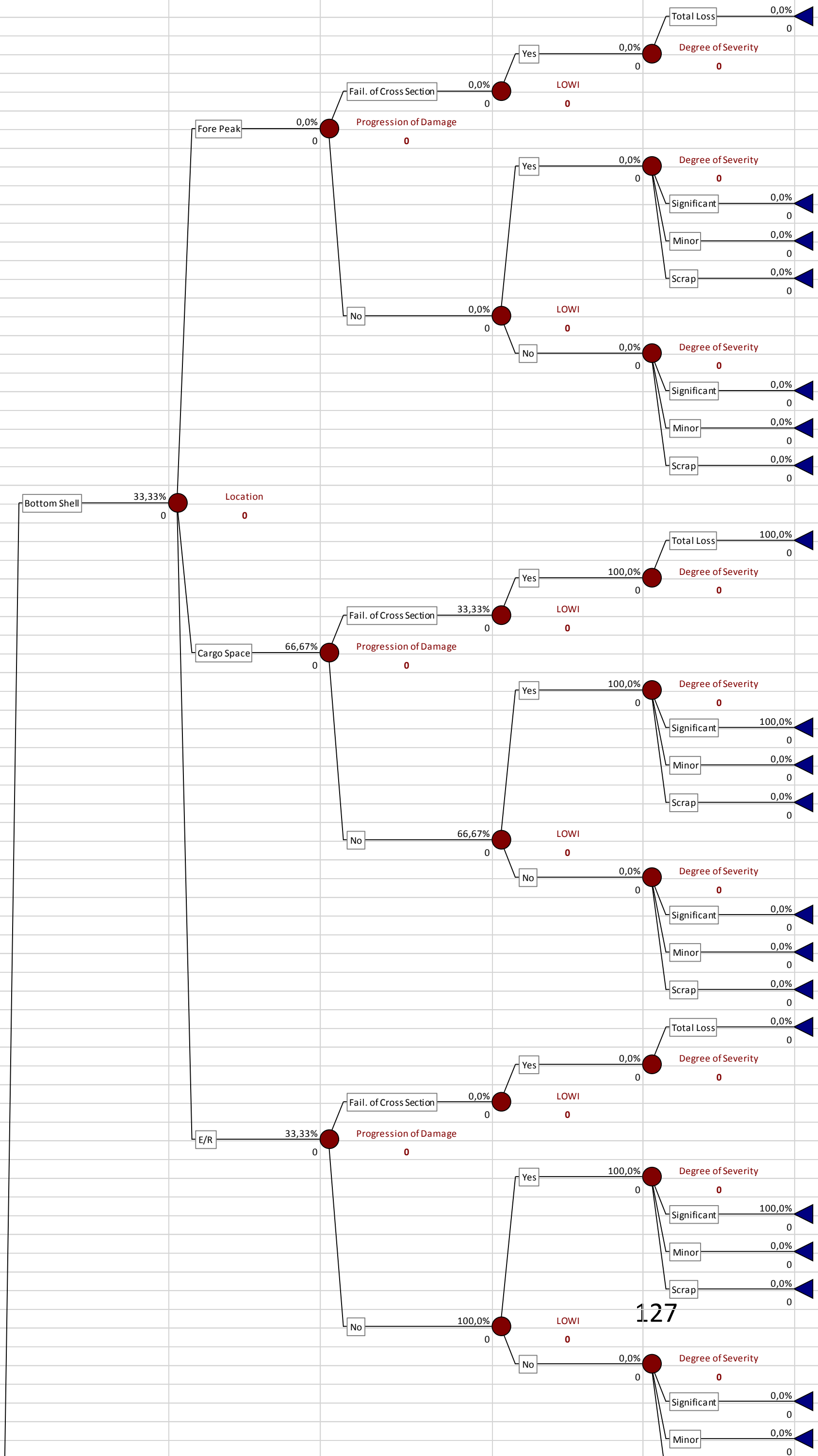


0	0	0	0	0	0
0	0	120000	0	0	2999,078472
0	0	0	0	0	0
0	0	2101321	0	0	26254,50549
0	0	120000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	120000	0	0	19501,43578
0	0	0	0	0	0
0	0	1484368,9	0	0	18547,98432
0	0	120000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	120	3514646	0	1,500077909	43935,35686
2,4	0	120000	0,24004187	0	12002,0935
0	0	0	0	0	0
0	0	0	0	0	0
0	0	120000	0	0	1500,242934
0	0	0	0	0	0

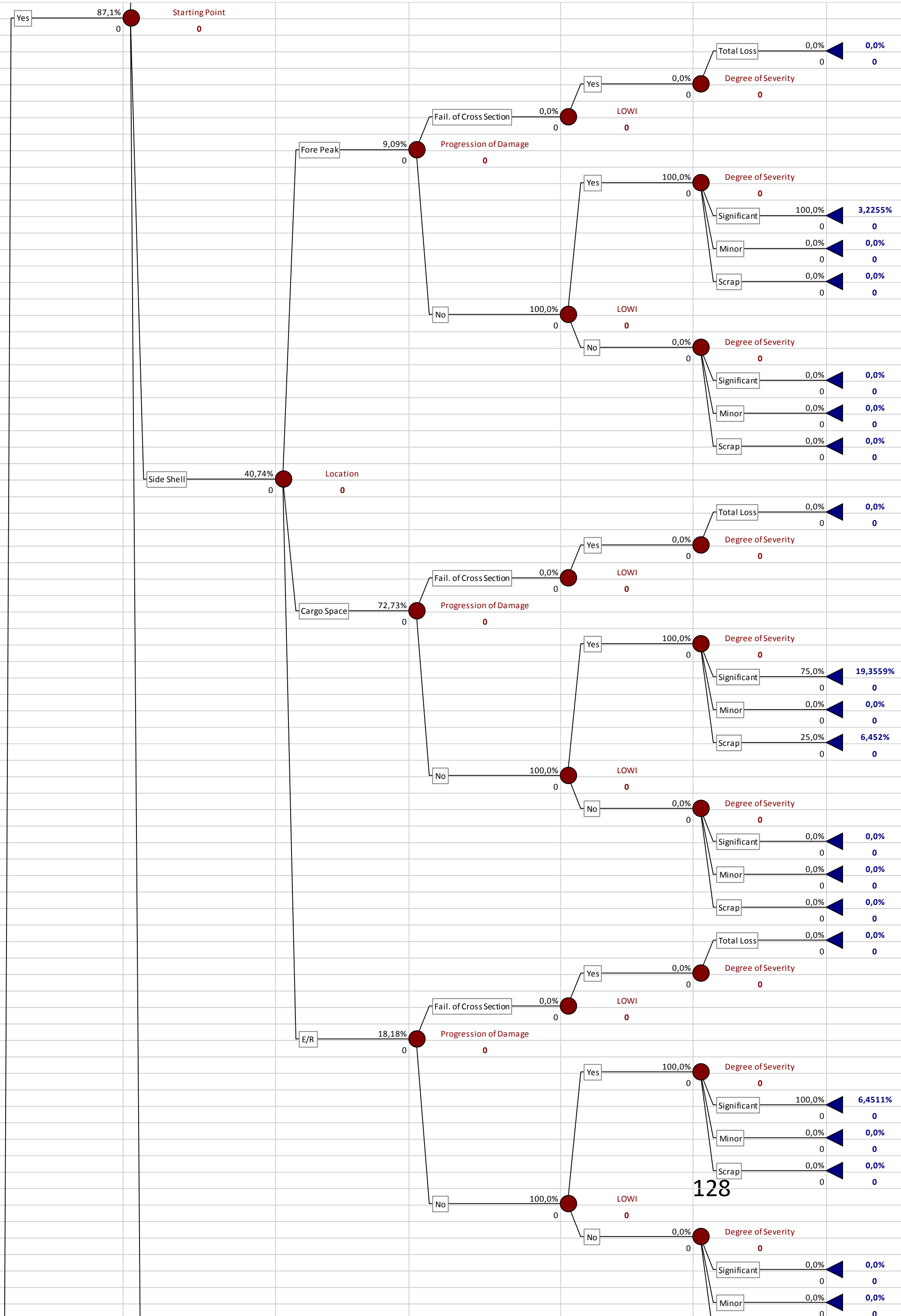

Total Loss 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Yes 0,0% 0 Degree of Severity 0
Fail. of Cross Section 0,0% 0 LOWI 0
Fore Peak 9,09% 0 Progression of Damage 0
Yes 100,0% 0 Degree of Severity 0
Significant 100,0% 0 1,2496% 0 | 0 0 120000 0 0 1499,505215
Minor 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Scrap 0,0% 0 0,0% 0 | 0 0 0 0 0 0
No 100,0% 0 LOWI 0
No 0,0% 0 Degree of Severity 0
Significant 0,0% 0 0,0% 0 | 0 0 120000 0 0 0
Minor 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Scrap 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Exterior Deck Plating 15,71% 0 Location 0
Total Loss 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Yes 0,0% 0 Degree of Severity 0
Fail. of Cross Section 0,0% 0 LOWI 0
Cargo Space 63,64% 0 Progression of Damage 0
Yes 100,0% 0 0
Significant 85,71% 0 7,4983% 0 | 0 0 120000 0 0 8997,995325
Minor 14,29% 0 1,2502% 0 | 0 0 0 0 0 0
Scrap 0,0% 0 0,0% 0 | 0 0 0 0 0 0
No 100,0% 0 LOWI 0
No 0,0% 0 Degree of Severity 0
Significant 0,0% 0 0,0% 0 | 0 0 120000 0 0 0
Minor 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Scrap 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Total Loss 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Yes 0,0% 0 Degree of Severity 0
Fail. of Cross Section 0,0% 0 LOWI 0
E/R 27,27% 0 Progression of Damage 0
Yes 100,0% 0 Degree of Severity 0
Significant 100,0% 0 3,7488% 0 | 0 0 120000 0 0 4498,515644
Minor 0,0% 0 0,0% 0 | 0 0 0 0 0 0
Scrap 0,0% 0 0,0% 0 | 0 0 0 0 0 0
No 100,0% 0 LOWI 0
No 0,0% 0 Degree of Severity 0
Significant 0,0% 0 0,0% 0 | 0 0 120000 0 0 0
Minor 0,0% 0 0,0% 0 | 0 0 0 0 0 0



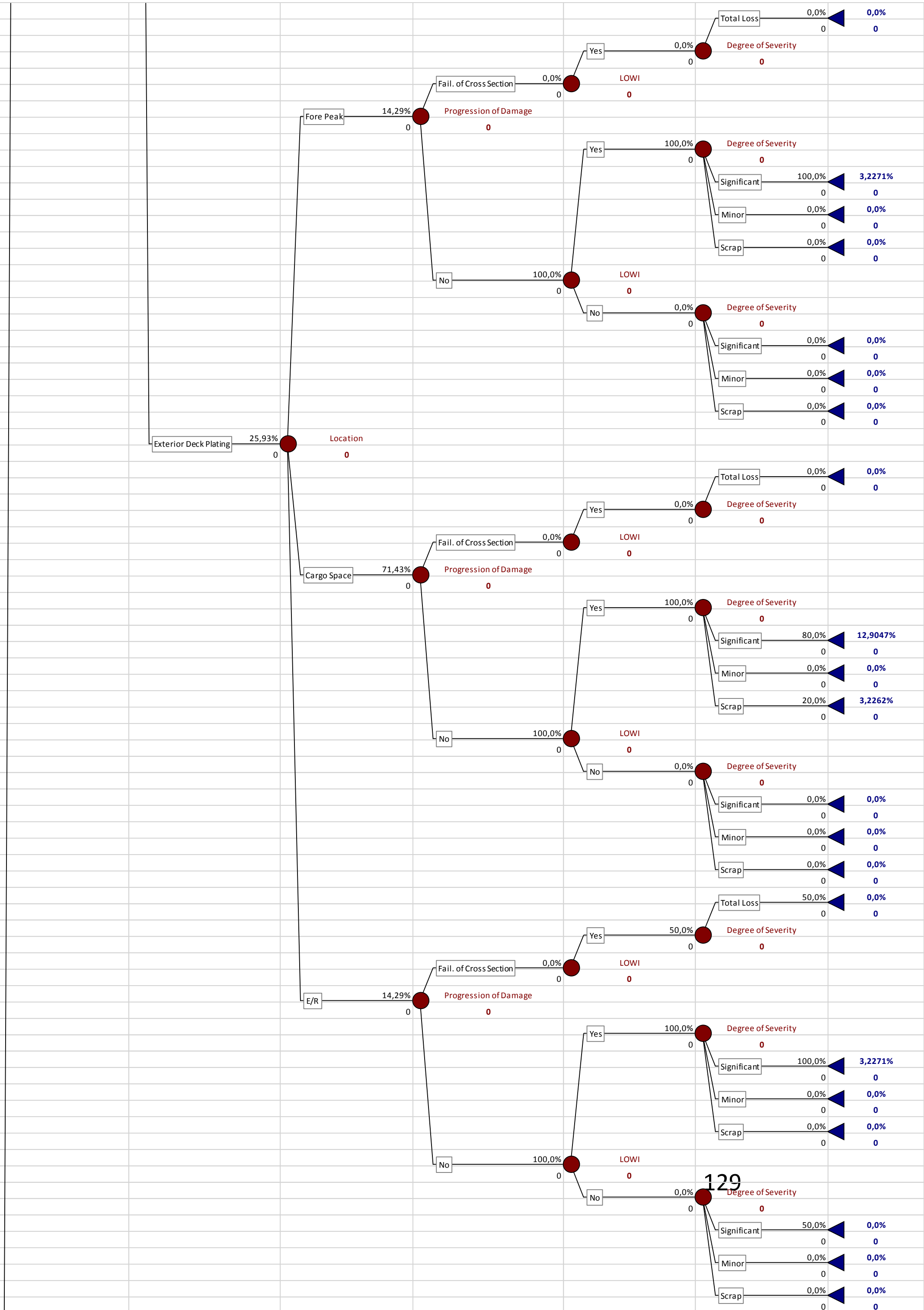
0	0	0	0	0	0
0	0	120000	0	0	6000
0	0	0	0	0	0
0	0	9166998,7	0	0	114587,4838
0	0	0	0	0	0
0	0	120000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	120000	0	0	1500
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	120000	0	0	1500
0	0	0	0	0	0
0,05	0	7135259,85	0,00125	0	178381,4963
0	0	0	0	0	0
0	0	120000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	120000	0	0	0
0	0	0	0	0	0



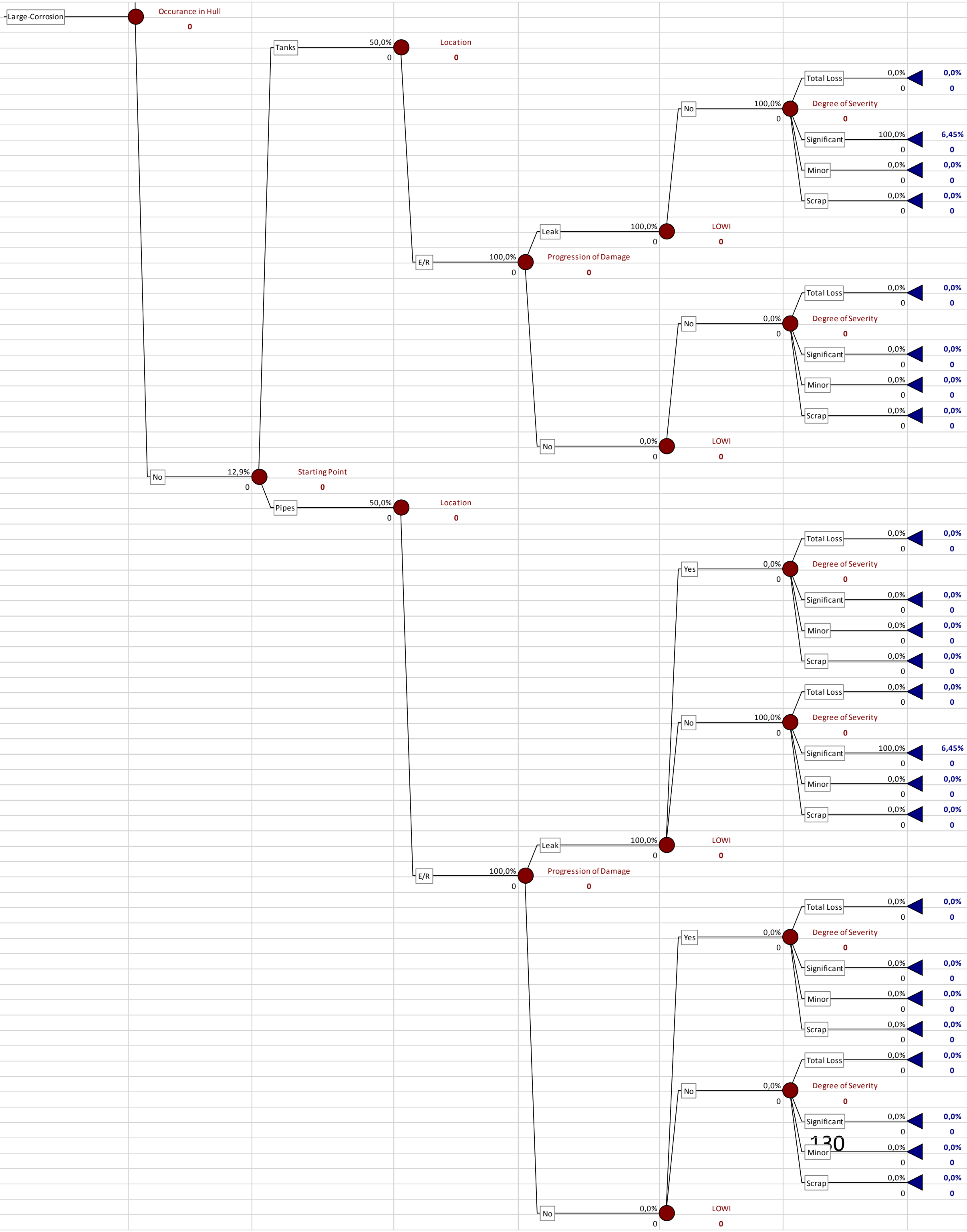
Probability	Fatalities	Environmental Impact	Damage to property	PLL	PEI	PDTS
0,0%	0	0	0	0	0	0
0,0%	0	0	300000	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	300000	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
6,4509%	0	120	15200709,5	0	7,741060889	980580,1483
12,9037%	0	0	300000	0	0	38711,11082
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	300000	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
9,6758%	0	0	300000	0	0	29027,52696
0,0%	0	0	0	0	0	0
0,0%	0	0	0	0	0	0
0,0%	0	0	300000	0	0	0
0,0%	0	0	0	0	0	0



Total Loss	0	0	0	0	0	0
Significant	0	0	300000	0	0	9676,634058
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0
Significant	0	0	300000	0	0	0
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0
Total Loss	0	0	0	0	0	0
Significant	0	0	300000	0	0	58067,78837
Minor	0	0	0	0	0	0
Scrap	0		12943471,5	0	0	835109,7376
Significant	0	0	300000	0	0	0
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0
Total Loss	0	0	0	0	0	0
Significant	0	0	300000	0	0	19353,26812
Minor	0	0	0	0	0	0
Scrap	0	0	0	0	0	0
Significant	0	0	300000	0	0	0
Minor	0	0	0	0	0	0



0	0	0	0	0	0
0	0	300000	0	0	9681,234238
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
1		300000	0,129046991	0	38714,09722
0	0	0	0	0	0
0		34571320	0	0	1115331,203
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	9681,234238
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0



0	0	0	0	0	0
0	0	300000	0	0	19350
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	19350
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	300000	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
			0,12905	7,74106	3182633,98280