# Bowtie Models as Preventive Models in Maritime Safety

## Bachelor's Final Degree Project

Facultat de Nàutica de Barcelona
Universitat Politècnica de Catalunya

Candidate:
**David Vergés Guri**

Supervised by:
**Dr. Jaime Rodrigo de Larrucea**
**Sandra Lielbarde**

**Bachelor's Degree in Nautical Sciences and Maritime Transport**

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# Acknowledgements

In the first place I would like to thank the University, which is not very usual, for having given me the opportunity to earn my life in an honest way during some years. Thus, I must thank Barcelona Tech (UPC) for having formed me in the past century as a Civil Engineer (I finished my studies in 1996, beginning with the boom of internet). It could be considered that I do not have to thank the University (and thus all its staff) since it is a case of *quid pro quo*(something for something): I study the subjects and pay the fees, and I am given the title, but it is always well-natured to be thankful for the good things. So I thank all the teachers who taught me their best with the means at their disposition.

Due to the global crisis I took the decision (that surely I would not have taken otherwise) to study a second career (somewhat related to the first since my expertise was ports and harbors). This time fully in the twenty-first century and also at Barcelona Tech (at another building fortunately: the precious building of Portal de la Pau, at the touristic and maritime heart of the city). I hope I will have the force and inertia to finish it, and for this I must thank also with all my heart the University where I am writing this words, the Latvian Maritime Academy or LJA, at Riga, also precious city and surroundings (more than Barcelona), where I am having the Erasmus experience that I did not have during my first career. An experience that while studying civil engineer I did not consider necessary but now I recommend to every student. Especially in this University (I really do not know others) where they treat Erasmus students excellently. Also, I had the opportunity to attend, invited, the 18th International Conference on Maritime Transport organized by the LJA in Riga where I could listen and later have access to state of the art papers that have been useful for this work, and an inspiration for future one.

I thank thus also all the staff of the LJA and specially VijaKasakovska, the head of the International Relations Department.

Next I must thank of course the two tutors of this project: Dr. Jaime Rodrigo de Larruceafrom Barcelona that has been also my professor during these almost four years now and who has introduced the taste for regulation and organization in my mind. It is true that my studies of Civil Engineering (pre-Bologna) were mainly physical-mathematical and thus very little time was dedicated to the knowledge of Law.

Also, I deeply thank also Prof. Sandra Lielbarde from LJA who has kindly advised my work at Riga and has given me her time each week (without having the obligation), and who has taught me the value of planning and the importance of the modern scientific method (that Internet has changed forever), which begins with a rigorous search and citation of sources. Also her many suggestions have been very important in pushing forward this document, since I must recognize I was not used to producing long documents and fortunately I have had her advice.

Finally, I would also like to dedicate this work to David Bowie (born David Jones, not Bowtie) for his music during all these years. I was not really a very big fan of his music and did not buy all his albums (only some for gifts) but with his loss (January this year 2016) I have realized that he has been a good company all these years (always there, his career began before I was born) and his hard work and high

standards have been an inspiration for me. And also working till the end and enjoying every moment, it seems. And May God's Love Be With Us.

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# Resumen

Este trabajo partió de una propuesta del Dr. Rodrigo de Larrucea que ha acabado de publicar un libro ambicioso sobre Seguridad Marítima. Como él mismo dice, el tema "excede con mucho las potencialidades del autor", así que en mi caso todavía es más cierto. Se puede aspirar a aportar una modesta contribución al estudio y difusión de la seguridad de la cultura marítima, que sólo aparece en las noticias cuando suceden desastres muy puntuales.

En cualquier caso, el profesor me propuso que me centrase en los *Bowtie Models*, modelos en pajarita, que integran el árbol de causas y el de consecuencias (en inglés el *Fault Tree Analysis*, FTA, y *Event Tree Analysis*, ETA). Ciertamente existen otras metodologías y aproximaciones (y en su libro presenta varias, resumidas), pero por su sencillez conceptual y posibilidad de generalización e inducción de resultados es una buena apuesta. Así, tras una fase de meditación y recopilación de información, me decidí a presentar un modelo en pajarita muy general donde hay cabida para las principales causas de accidentes (factores ambientales, error humano y fallo mecánico), sin menoscabo de que pueda existir una combinación de causas.

Sin embargo, a la hora de explotar este modelo existe la gran dificultad de dar una probabilidad de ocurrencia, un número entre 0 y 1, a cada rama. Normalmente las probabilidades de ocurrencia son pequeñas y por ello difíciles de estimar. Cada accidente es distinto, grandes catástrofes hay pocas, y cada accidente ya es estudiado de manera exhaustiva (más exhaustiva cuanto más grave). Otro factor que dificulta la estima de la probabilidad de fallo es la evolución constante del mundo marítimo, tanto desde el punto de vista técnico, de formación, legal y hasta generacional pues cada generación de marinos es distinta. Los esfuerzos están enfocados a aumentar la seguridad, aunque siempre con un ojo puesto en los costes. Así pues, he presentado modelos en pajarita con su valor didáctico y gráfico pero sin entrar en detalles numéricos, que posiblemente en el ejercicio de la profesión ya podré ir afinando e interiorizando.

En este trabajo también he intentado no mantenerme totalmente en el lado teórico (ya sabemos que si todo se hace perfecto, todo sale bien, etc…) y así presento con cierto detalle 2 casos bien conocidos de accidente marítimo: el del petrolero Exxon Valdez, en 1989 y el del ferry (ROPAX) Estonia en 1994, entre otros que se nombran de pasada. Casos ya algo viejos pero que contribuyeron a aumentar la cultura de la seguridad, hasta el nivel de que gozamos actualmente, por lo menos en los países occidentales. Pues la seguridad, como comenta Rodrigo de Larrucea "*es una actitud y nunca es fortuita; siempre es el resultado de una voluntad decidida, un esfuerzo sincero, una dirección inteligente y una ejecución cuidadosa. Sin lugar a dudas, siempre supone la mejor alternativa*".

# Resum

Aquest treball ha sorgit d'una proposta del Dr. Rodrigo de Larrucea que ha acabat de publicar un llibre ambiciós sobre Seguretat Marítima. Com ell mateix diu, el tema "excedeix amb molt les potencialitats de l'autor", així que en el meu cas això és més cert. Es pot aspirar, però, a fer una modesta contribució a l'estudi i difusió de la seguretat de la cultura marítima, que només apareix a les notícies quan tenen lloc desastres molt puntuals.

En qualsevol cas, el professor em va proposar que em centrés en els *Bowtie Models*, models en corbatí, que integren l'arbre de causes y el de conseqüències (en anglès el *Fault Tree Analysis*, FTA, i l'*Event Tree Analysis*, ETA). Certament, existeixen altres metodologies i aproximacions (i en el seu llibre en presenta vàries, resumides), però per la seva senzillesa conceptual i possibilitat de generalització i integració dels resultats era una bona aposta. Així, després d'una fase de meditació i recopilació de informació, em vaig decidir a presentar un model en corbatí molt general on caben les principals causes d'accidents (factores ambientals, error humà i fallada mecànica), comptant també que pot existir una combinació de causes.

De tota manera, a l'hora d'explotar aquest model existeix la gran dificultat de donar una probabilitat de ocurrència, un nombre entre 0 i 1, a cada branca. Normalment les probabilitats d'ocurrència són petites i degut a això difícils d'estimar. Cada accident és diferent, de grans catàstrofes n'hi ha poques, i cada accident ja és estudiat de manera exhaustiva (més exhaustiva quan més greu és). Un altre factor que dificulta l'estima de la probabilitat de fallada és l'evolució constant del món marítim, tant des del punt de vista tècnic, de formació, legal i fins i tot generacional doncs cada generació de marins és diferent. Els esforços estan doncs enfocats a augmentar la seguretat, encara que sempre amb un ull posat sobre els costs. Així, he presentat un model en corbatí pel seu valor didàctic i gràfic però sense entrar en detalls numèrics, que si s'escau ja aniré afinant i interioritzant en l'exercici de la professió.

En aquest treball també he intentat no mantenir-me totalment al costat de la teoria (ja se sap que si tot es fa bé, tot surt perfecte, etc…) sinó presentar amb cert detall 2 casos ben coneguts d'accidents marítims: el petroler Exxon Valdez, el 1989 i el ferry Estonia en 1994, entre altres esmentats. Són casos ja una mica vells però que van contribuir a augmentar la cultura de la seguretat, fins a arribar al nivell del que gaudim actualment, al menys als països occidentals. Doncs la seguretat, com esmenta Rodrigo de Larrucea *"és una actitud i mai és fortuïta; sempre és el resultat d'una voluntat decidida, un esforç sincer, una direcció intel·ligent i una execució acurada. Sens lloc a dubtes, sempre suposa la millor alternativa"*.

# Abstract

The work has been inspired in its initial aspects by the book of my tutor Jaime Rodrigo de Larrucea, that presents a state of the art of all the maritime aspects related to safety. Evidently, since it covers all the topics, it cannot deepen on every topic. It was my opportunity to deepen in the Bowtie Model but finally I have also covered a wide variety of topics.

Later, when I began to study the topics, I realized that the people in the maritime world usually do not understand to a great extent statistics. Everybody is concerned about safety but few nautical students take a probabilistic approach to the accidents. For this it is extremely important to study the population that is going to be studied: in our case the SOLAS ships

Also, during my time at Riga, I have been very concerned with the most diverse accidents, some of them studied during the courses at Barcelona. I have seen that it is difficult to model mathematically the accidents, since each one has different characteristics, angles, and surely there are not 2 equal.

Finally, it was accorded that I should concentrate on the Bowtie Model, which is not very complex from a statistical point of view. It is simply a fault tree of events model and a tree of effects. I present some examples in this Chapter 2. The difficulty I point out is to try to estimate the probabilities of occurrence of events that are unusual.

We concentrated at major accidents, those that may cause victims or heavy losses. Then, for the sake of generality, at Chapter 4, I have divided the causes in 4 great classes: Natural hazards, human factor, mechanical failure and attacks (piracy and terrorism). The last concern maybe should not be included beside the others since terrorism and piracy acts are not accidents, but since there is an important code dedicated to prevent security threats, ISPS, it is example of design of barriers to prevent an undesired event (although it gives mainly guidelines to follow by the States, Port Terminals and Shipping Companies). I have presented a detailed study of the tragedy of the Estonia, showing how a mechanical failure triggered the failure of the ferry, by its nature a delicate ship, but there were other factors such as poor maintenance and heavy seas.

At the next Chapter, certain characteristics of error chains are analyzed. Finally, the conclusions are drawn, offering a pretty optimistic view of the safety (and security) culture at the Western World but that may not easily permeate the entire World, due to the associated costs.

# Key Words

Maritime safety, security, accidents, models of accidents, Fault Tree Analysis, Event tree Analysis, Tree of Causes, Tree of Events, Bowtie Model, Exxon Valdez, MV Estonia, Natural Hazards, Freak Waves, Tsunamis, Human Factor, Piracy, Terrorism, Chains of Errors, Bridge Team Management, Watchkeeping, Management of Safety in Shipping, Bayes' Theorem, Wave Equation.

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# Table of contents

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# List of Figures

# List of Tables

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# BOWTIE ANALYSIS AS PREVENTIVE MODELS OF MARITIME SAFETY

# Chapter 1: Introduction

Accidents at sea are still one of the main problems of maritime transport (for its economic and ecologic cost, besides the tragic loss of human lives). Even though with the years the accidents at sea have been greatly reduced (mainly in percentage), the bad news of accidents continue leaking, be it at ships that supposedly comply with the highest standards, adapted theoretically to the last technical advances and with a crew (Costa Concordia, Sewol) as at the actually sadly famous "*pateras*" used by immigrants and refugees that tragically sink at Mediterranean waters. However, in this work we are going to deal with IMO ships, with gross tonnage more than 500 and accordingly subject to the international ships' safety standards (SOLAS ships). We are not going to deal with small fishing boats or passenger vessels (and evidently, military vessels) that do not comply with SOLAS.

The main aim of this work is to make a revision of the methods to prevent and study the fails that may cause accidents and near misses. The bowtie model offers a good approach, since at one side (the left-hand) are the causes thatmay cause an accident, and at the right the consequences. In these bowtie models it is also of great importance the design of barriers, systems or procedures to avoid or mitigate the causes and consequences of a branch of this model.

In order to study the accidents and its prevention it is adequate to study the "*universe*" where they are taking place.

Currently (according to the data of UNCTAD and Lloyd's register as has been presented by Correa, 2016[1]), there are (as January 2016) a total of 59.436 IMO ships (>300 GT and passenger ships >100 GT) with a total carrying capacity of 1727 million DWT (see Figure 1).

In 2007 the world fleet of merchant ships for the first time exceeded 1000 million DWT (1,090).

In the last 25 years the supply capacity of merchant ships has almost multiplied by 1.5. Its growth has been over 70% in the last 10 years and 5% in the last year.

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[1]Correa, F. (2016):*Maritime transport. Seaborne trade and merchant fleet*. Presentation at the Latvian Maritime Academy, LJA (Riga, Latvia).

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# World merchant fleet by ship type

| Detail | Total DWT | Total GT | Total TEU | Total HP | Av age | no of ships |
|--------|-----------|----------|-----------|----------|--------|-------------|
| Grand Totals Bulker | 766.213.224 | 422.310.983 | 79.569 | 30.416.453 | 10,8 | 11.338 |
| Grand Totals tanker | 606.335.543 | 367.662.953 | 3.063 | 135.115.180 | 16,9 | 15.808 |
| Grand Totals container | 244.980.973 | 215.636.583 | 19.771.546 | 89.553.898 | 11,6 | 5.208 |
| Grand Totals combination | 1.528.500 | 924.074 | 0 | 316.577 | 29,5 | 59 |
| Grand Totals dry cargo | 74.538.342 | 54.139.225 | 1.762.417 | 40.954.943 | 24,4 | 15.042 |
| Grand Totals ferry/pass | 6.700.847 | 38.249.656 | 14.900 | 51.792.841 | 27,2 | 7.214 |
| Grand Totals reefer | 5.933.911 | 6.492.083 | 57.955 | 8.288.613 | 29,2 | 1.814 |
| Grand Totals roro | 21.265.314 | 50.847.214 | 281.685 | 25.272.630 | 17,8 | 2.953 |
| Grand Grand Totals | 1.727.496.654 | 1.156.262.771 | 21.971.135 | 381.711.135 | 18,9 | 59.436 |

**Jannuary 2016**

**Figure 1:** World merchant fleet by ship type (Correa, 2016). It may be observed that the oldest ships are the combination (which are not very significant in number), the reefers and the ferries/passenger, that are in their late twenties. The newest are the bulkers and the containerships.

According to IUMI, International Union of Maritime Insurance that present their statistics yearly[2](each spring) including comments, which is very useful to follow trends. The next figures are directly from this reference, as the following interpretation.

"*The general trend in reducing frequency of total losses witnessed over the past 14 years reversed in 2015. Total loss frequency at an all-time low in 2014, increasing during 2015.*

*By number of vessels, notable increase in container vessel, bulker and tanker tonnage.*

*Whilst tanker and bulker tonnage has shown an overall downward trend in Total Loss since 1999, the container fleet has suffered an increase in total loss frequency by number of vessels.*

*Passenger and non-cargo categories show a significant reduction in Total Loss frequency in 2015.*

*The world bulker and tanker fleets show a marked reduction in total loss of older tonnage (15 years plus) in more recent years (2011-15).*

*There is a marked increase in the frequency of total loss caused by heavy weather and grounding.*

Heavy weather:     2001 – 2005: 30%          2011 – 2015 45%

Grounding:     2001 – 2005: 16%          2011 – 2015 26% "

At the reference there are more commentaries, but no proposals or deep analysis of the causes.

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[2]http://www.iumi.com/committees/facts-a-figures-committee/statistics
http://www.iumi.com/images/documents/2016-04-Statistics/IUMI_2015-2016-Casualty_and_World_Fleet_Statistics-Analysis_Spring_2016.pdf

## Total Losses 1999 – 2014
### By Number (vessels > 500 GT)
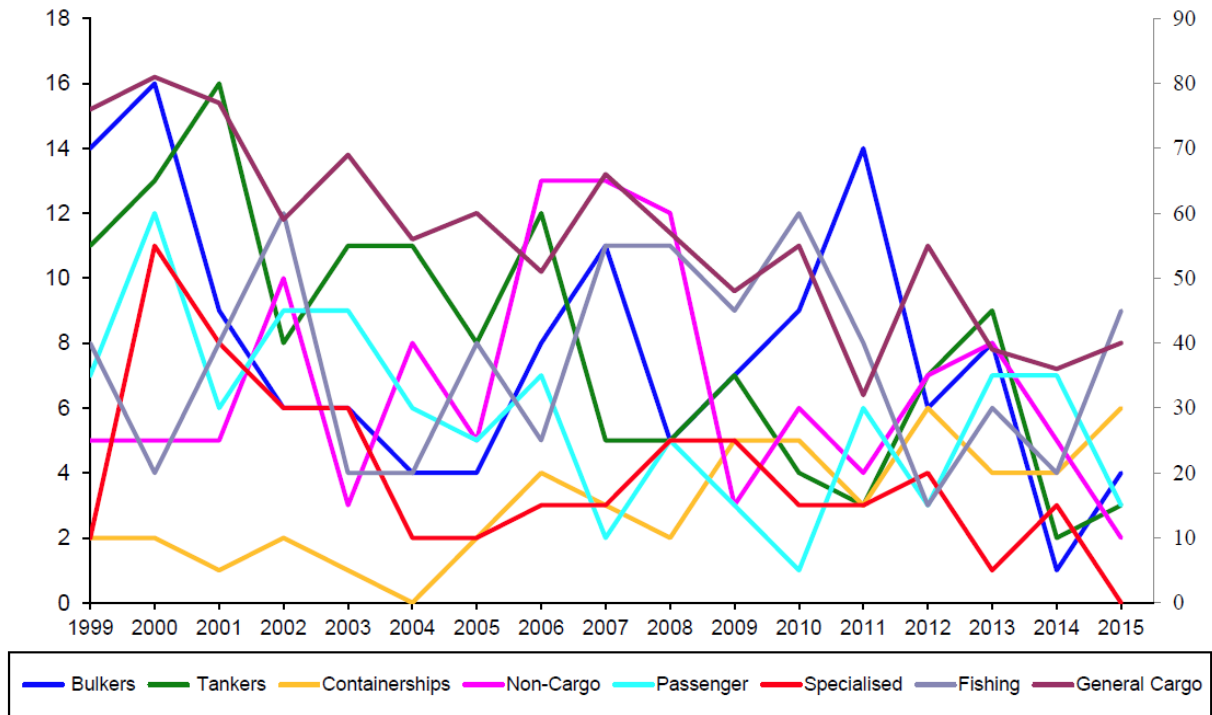


Source: LLI, total losses as reported in Lloyds List

**Figure 2:** Total losses 1999-2015, as reported by Lloyds List (Source IUMI). The data is compiled the 1st January 2016. The scale is at the left.
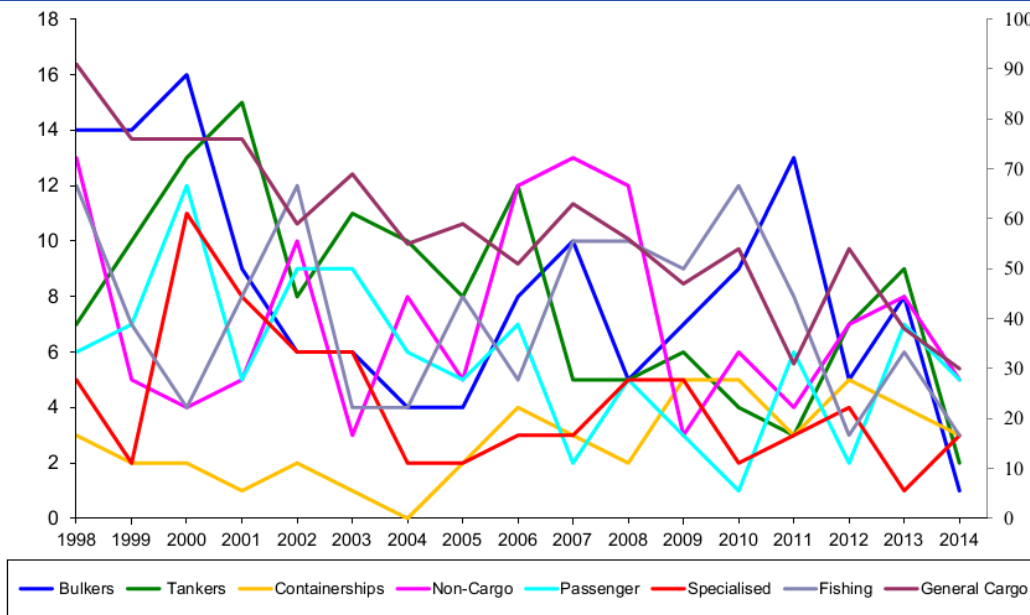
**Figure 3:** Total losses 1998-2014. It is similar to the previous, with some change.

Hull losses show a general downward trend in total loss frequency for most vessel types. The frequency of total loss since 1997, as a percentage of the world fleet, continues to decrease and has more than halved by both the number of vessels and tonnage. We may observe that 2014 is the best year ever with only 33 total losses (Figure 1). At Figure 2 the number of losses in 2014 is only 27, but this is because some losses were not still included in the statistics still (since the data is updated beginning each year). Counting the losses of 2015 in Figure 1, there are 35 total losses, so we must expect the total losses to increase also by 6 units, so it could be 41 (increasing, in any case). In 2013 there were 50 total losses, which is not a small number since the ships are always over 500 GT.
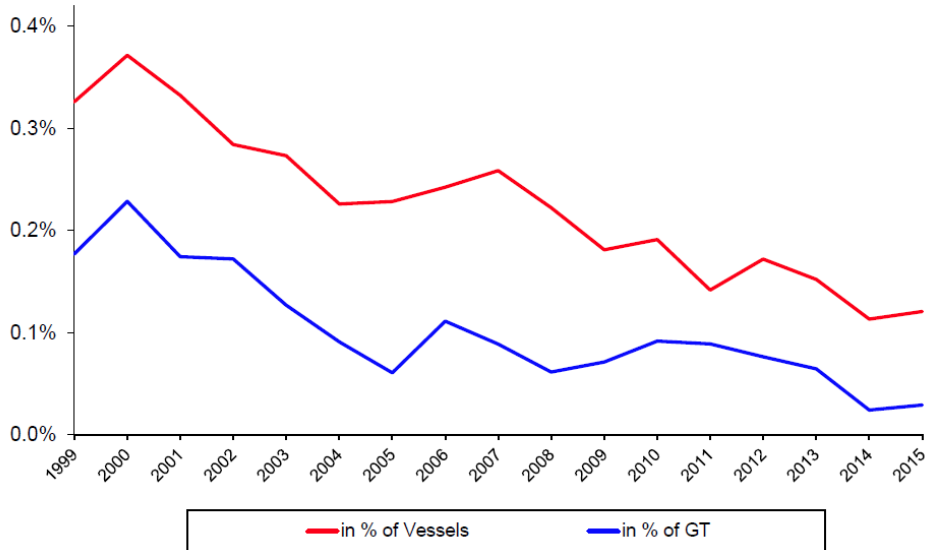
**Figure 4:** Total losses of vessels, as a percentage of tonnage (1999-2015). The data of 2015 may still increase.

It may be observed that total losses have been cut to more than a half in 15 years. The effect of the 2011 tsunami of Japan is not seen at this figure since it did not affect the biggest ships (the affected ports were small fishing ports usually, with few vessels over 500 GT).



**Figure 5:** The same data as before, years 1998-2014. It must be noted, as before, that 2014 is the best year ever, in a scenario of always increasing world tonnage.
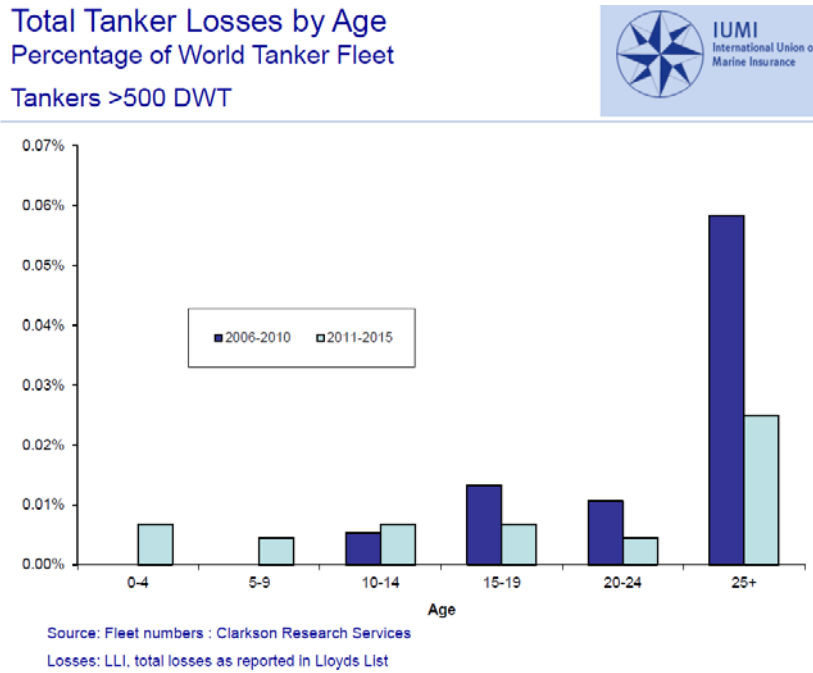
**Figure 6:** Total tanker losses by age, as a percentage of the world tanker fleet.

This is a very interesting figure since it shows the effect of age in the total tanker losses depending on its age, divided between the years 2006-2010 and 2011-2015. The only great oil spill due to tankers in these dates was the case of *Hebei Spirit* in South Korea (2007) that was not a total loss since it was quickly repaired to cut spilling. Then, it must be assumed that most tankers were lost navigating on ballast water or they were small tankers (e.g. chemical tankers). Another fact to notice is that older tankers, 25 or more years old, contribute to the total losses as much as all the other newer vessels, approximately. Curiously, 25 years was the age of the Prestige, when it sank off the coast of Galicia in 2002. The losses have decreased sharply from the five-year period 2006-2010 to 2011-2015, especially in ships 25+. There are no losses in 2011-2015 of tankers 0-9 years old.
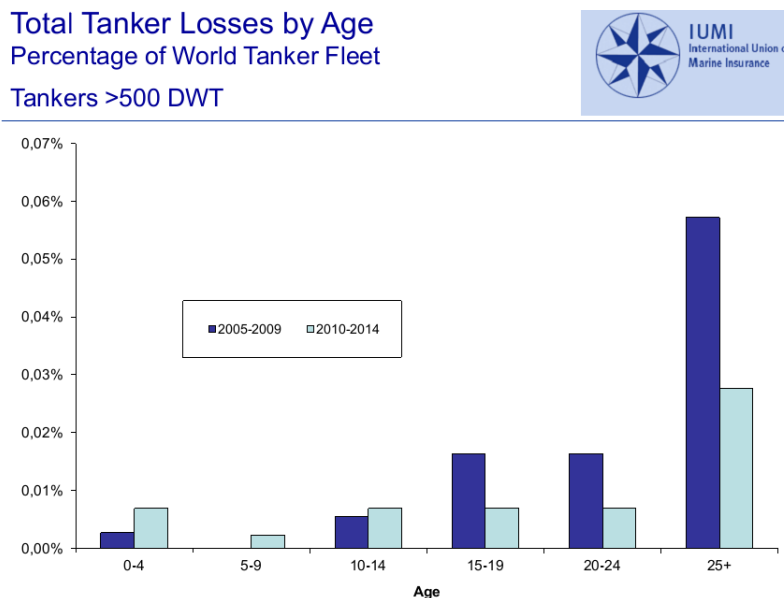


**Figure 7:** Tanker losses by age, updated to 2014. Oldest tankers are prone to total loss. It may be observed that the chart has some minor changes compared to the updated chart beginning 2016.

**Figure 8:** Serious incidents and total losses 1999-2015.

This figure is also very interesting since it shows the total losses and incidents by number of vessels (not GT like the previous figure, so a small vessel counts the same as supertanker). We observe that the number of incidents towers a peak of some 1000 serious incidents in the year 2007 (almost three daily, which seems inadmissible). In effect, it seems some measures were taken since these incidents have been cut to more than half since 2007. The total losses show a decreasing trend, as shown before, but increasing at 2015.



**Figure 9:** Incidents and total losses 1998-2014. The updating of the data shows the same decreasing tendency in 2014.
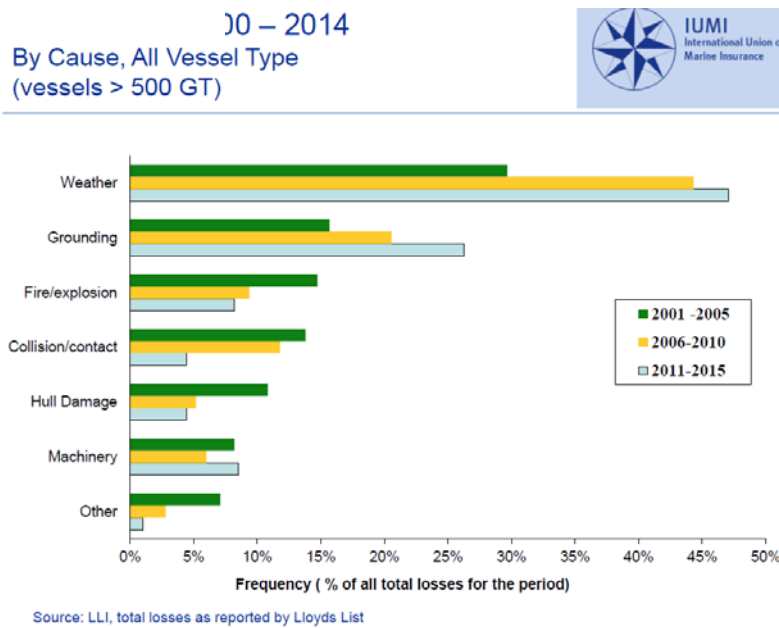
**Figure 10:** Total losses (2001-2015), by cause.

Here is an explanation of the causes of total losses.Since there is only a cause for loss in this analysis (in this case), for each period of 5 years, the percentages must add 100%. We may see that the main cause is weather, increasing these last years. Next is hull damage, also increasing. The rest of the causes are decreasing.
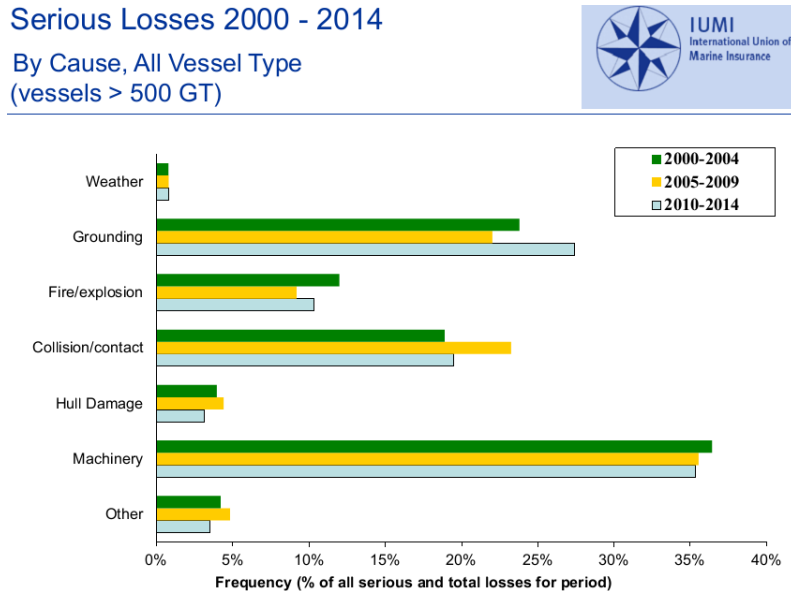


**Figure 11**: Serious Incidents and Total losses, by cause (2000-2014).

We may observe first that according to Figures 8 and 9 that serious losses are more numerous than total losses (by a factor of 10 approx.). Then it is explained that machinery is the main cause, since machinery failure is prone to cause serious losses, but few total losses. Weather is in this case a minor cause, which means that weather causes total losses but not serious losses. It is also possible that the methodology has changed in the last chart.
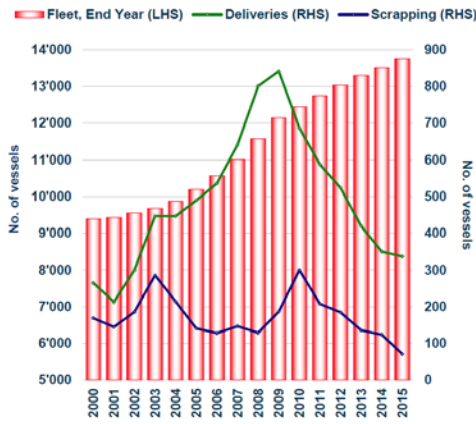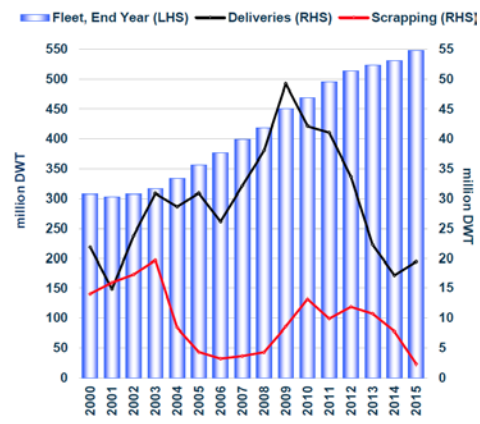
**Figure 12**: Historical development of tanker fleet, 2000-2015 (also from the referenced document of statistics of the IUMI [2]).

This is a very interesting chart since we may see how the world fleet of tankers keeps growing even though the peak of deliveries in 2009 (and thus, an inflection point in the total) was attained with the breaking of the global crisis of 2008. In 2013, the number of tankers delivered continues to decrease and is in the levels of 2002. Another easy calculation we must make from these chart is that if some 350 tankers were delivered in 2013 and this is some 22 million DWT, then the mean tanker delivered in 2013 some 63.000 DWT. And if the total number of vessels was 13250 and the total tanker fleet DWT in 2013 was 525 million DWT the mean tanker is some 40.000 DWT (which means that new-built tankers are somewhat larger than existent ones). However, the last tendency is to increase the deliveries in 2015 and decrease the scraping.
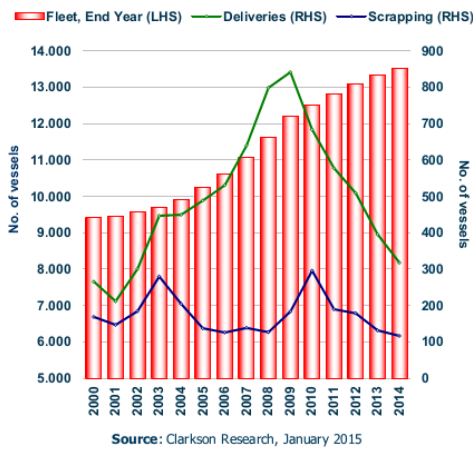
## Tanker Fleet
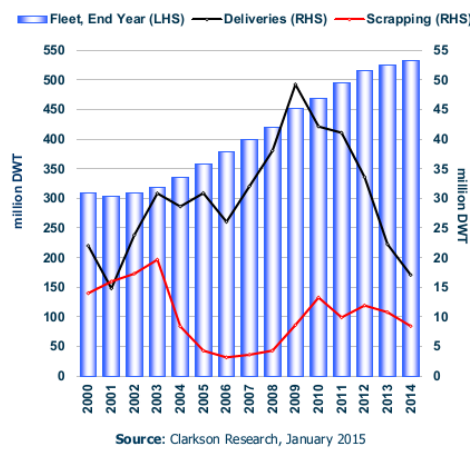


**Figure 13**: Historical development of tanker fleet (2000-2014).

The data to 2014 shows the number of new deliveries still decreasing after the global crisis but at a slower rate. This positive effect is more notable in the total Dead Weight Tonnage than in the number of ships, which means the new ships are comparatively bigger.



**Figure 14**: Average age of the World Fleet. Includes all vessels above 100 GT.

In this chart we may observe that the average of all World Fleet is pretty constant through the years 2000-2016, some 20 years with a tendency of slight growth. The ''other ship" type, with an average age of almost 25 years, pulls the average up (although they may be smaller in GT than other types).

After having presented to a certain extent the population or universe of our study, we will begin presenting the most common factors in groundings and collisions. The data has been collected and analyzed by Acar *et al* (2007), which concentrates in accidents associated with human error or inappropriate

**Common Factors in Groundings**
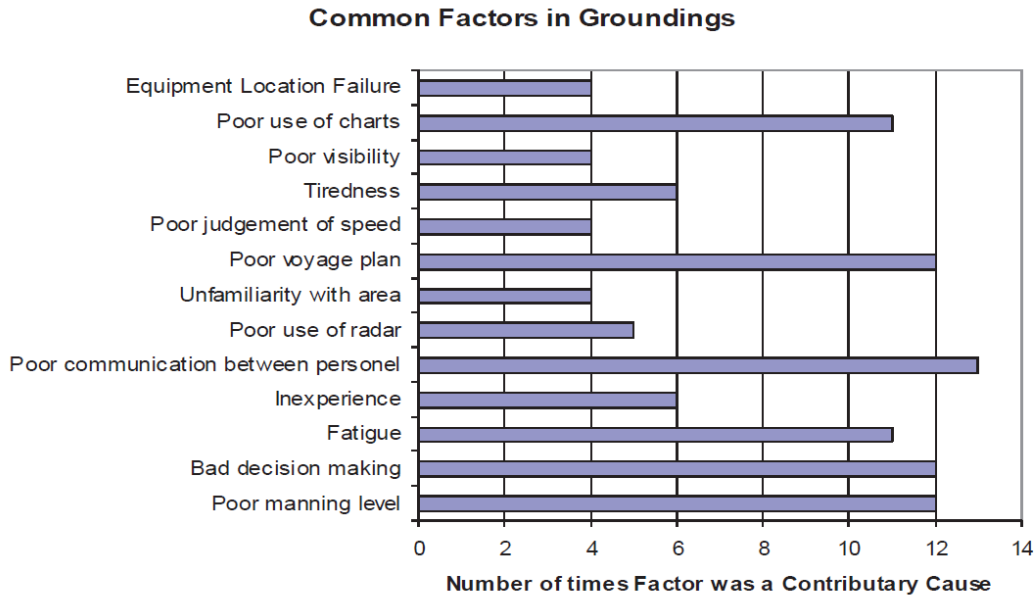


**Figure 15**: Common factors in groundings (from Acar *et al*, 2007).

**Common Factors in Collisions**
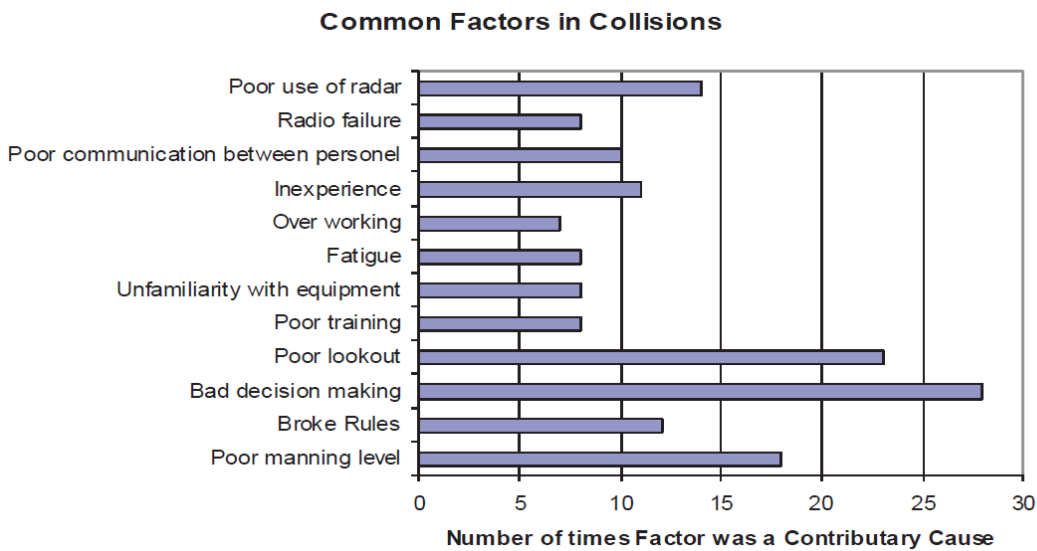


**Figure 16**: Common factors in collisions (from Acar *et al*, 2007)

# Chapter 2: Modeling Accidents

## 2.1. Models of Accidents

The investigation on Safety has been planned according to the models that integratethe General Theory of Safety: theTheory of accidents (accident models) and Risk Analysis. The Risk Analysis usually considers the cost of an accident (the risk is defined as the probability of an accident multiplied by its cost).

The comprehensiveness and the features of each model will determine our capacity of identifying and taming the dangers, and hence prevent accidents.On this base there are three types of accident analysis,as shown in Rodrigo de Larrucea(2015):

-Sequential: explain the causes of accidents as a result of a chain ofdiscrete events that occur in a determined temporal sequence.The events at these models have a linear and direct relation.

- Epidemiologic: describe the events that give origin to an accident in the same way as how a disease spreads. This gives, as a result, a combination of factors, some manifested and other latent, that coincide in space and time.

-Systemic: the accident appears as a result of the variability of a complex system, as a result of interactions and unexpected combinations of actions.

One of the main differences between the systemic model and the sequential analysis consists in the fact that the first describes a process of accident, through a complex and interconnected net of events while the last defines itas a simple chain of causes and effects.

The study of these accidents can be done from the point of view of the models from the accident theory (accident model) or from the risk analysis (risk models).The aim is in the first place to prevent non-desired effects or, if this is not possible, its mitigation. Accidents are defined as unexpected occurrences that cause lesions, death, loss of production or harms goods. Researchers of different fields of science (mainly those dedicated to industrial safety) have developed all these theories finally avoid all and accidents.

## 2.2. Sequential Model

W.H.Heinrich (1931) developed the theory named "domino effect". According to him, an accident is originated by a sequence of facts, (like domino pieces falling). Heinrich proposed a "sequence of five factors in the accident". Here they are:

-Heritage and social environment

-Unsafe action

-Human error

-Accident

-Harm

The elimination of one of the pieces would interrupt the sequence and the one that sees more easy to secure is the third, the Human Error, since unsafe actions and accidents are latent at the industrial organization. According to its empiric experience, for every tragic accident with important wounds there were 30 with minor wounds and 300 "accidents without wounds". On this base the theory of incidents is built (near misses) that luckily do not develop to accidents. Heinrich did not offer data to back his theory, but presents a useful starting point.

### 2.2.1.Fault Tree Analysis, FTA

Developed originally in 1962 at the Bell Laboratories, to evaluate the reliability of the Minuteman missile, the fault trees are a technique very used sinceit givesqualitative and quantitativeresults. The risk is evaluated going backward at an event chain.

The qualitative technique consists in a deductive process based in Boole's algebra laws, which allow the expression of complex occurrences in function of the errors or basic occurrences. Some will be more improbable since they will require the simultaneous occurrence of 2 or more events and others more probablewill require only one event. The complex undesired event is named TOP since it is represented on top.

### 2.2.2. Event Tree Analysis, ETA

A tree of events shows a progression sequence, a sequence of final states and specific causes through time. We work with logic, following a forward time line. It does not require the premise of a known danger

### 2.2.3. Bowtie models

The model is built from the combination of a tree of faults and a tree of events, so it integrates the elements that cause the error with its respective probabilities and in the same way the possible consequences with its probabilities. Its representation is always with the causes at the left, the consequences at the right and the knot is the non-desired accident.

## 2.3. Epidemiologic Models: the Swiss Cheese

It was proposed originally by James T. Reason of the University of Manchester and has a wide acceptation.

In this model the defenses of an organization against an accident are modeled like a series of barriers represented by slices of cheese. The holes at the slices represent theflawsat the barriersthat vary in size

and position at each cut. The error is produced when the "*holes*" at each slice align, so the accident has a "*windowof opportunity*". Danger trespasses all the slices and this leads to a fail and an accident. The problem is thus that various errors occur at the same time.

The "holes" at the cheese may be active fails (human errors that have a brief temporal impact generally) and latent conditions, that are problems of the design of the system, generally occult.

## 2.4. Systemic Models

Opposing sequential models other systemic models appear, among them the social-theoretical of Rassmusen and, in a fundamental way, the STAMP (Systems-Theoretic Accident Model and Processes). On the other hand, on the perspective of the human factor there is the HFACS (Human Factor Analysis and Classification System). The sequential models of analysis are not suitable to understand the non-linear dynamic relations between the components of complex industrial systems, let alone a ship thatinteracts with nature. Models to analyze accidents in this way are based on the theory of systems, who describe the work of a system as a whole instead of concentrating at the basic level cause-effect.

In modern complex systems, human beings interact with technology to obtain results as a consequence. At the systemic models it is considered that accident appear from the interactions between the components of the system and do not derive of a single cause. Hence, the study is centered in the limitations, the lack of control and other dysfunctions of the systems or its processes. Under systemic models, accidents are the result of an inadequate control.

### 2.4.1. The social-technical model of Rasmussen. AcciMap model

Growing complexity and technology have given rise to developing systems to evaluate risks from a socio-technical point of view, characteristics of complex organizations that operate in dynamic environments. The human factor is still essential part of a complex system. In dynamic and very complex environments it is not possible to establish procedures for all the possible conditions, and particularly, for the case of highly unexpected risk situations.

The Model was developed originally by Rasmussen (1997), as a part of a strategic approach to risk management, but its main application has been as an instrument of analysis of accidents, specifically for the analysis of the causes of the accidents and the "near-misses" produced at complex socio-technical systems.

The exact format of the diagram varies in function of the aim of the analysis, but the lowest levels represent the immediate precursors to the event, in relation with the activities of the workers and the physical events, processes and conditions. The next levels use to represent the factors at the level of organization of the company. The higher levels usually include factors at social or governmental level that are external to the organization. The compilation of multiple factors and its interrelations, in a unique diagram, allows analysts to understand how and why the event took place and identifies the problematic areas that may by dealt with to increase the security of the system. A positive aspect of AcciMap model is its academic and docent use, since it enables to visualize in a simple way the causes, latent causes and previous relations in the system and subsystem.

**2.4.2. Human Factors Analysis and Classification System (HFACS)**

The HFACS (Human Factors Analysis and Classification System) identifies the human causes of an accident and is an instrument of great help in the process of investigation and focuses on the efforts of formation and prevention. It was developed by the doctors Shapell and Wiegmann, from the Institute of Medicine of Aviation and the University of Illinois. They showed that human error was a primary causal factor in 80% of the air accidents of the American Navy.

HFACS is based on the model of "Swiss cheese" of Reason and points four levels of active errors and latent misses:

Insecure acts

Previous conditions for insecure acts

An inadequate or unsafe supervision

Influences of organization

It is an integral study of human error, defining 19 causal categories in 4 levels of human failure. The HFACS exhaustively details the numerous active and latent fails that influence the performance of the operator and may cause the error.

HFACS allows professionals of security to identify all the factors that may cause human errors in complex environments. They assume a model related with the theory of the Swiss cheese, where an innovation is that the aspects of the organization are structured in 3 factors:

Resource management: It is related with decision-taking at organization level relating the assignation of the assets of the company.

Organizational climate: It is referred to the ambience at the work in the organization (structure, politics, culture, etc,..)

Operative process: Concerns the organizational decisions and the rules that control the quotidian activities at an organization (operations, supervision and control procedures, etc…)

This system represents the most complete approximation to the human factor and its connection with the organizational aspects and is also used at the maritime world.


**2.4.3. Systemic-Theoretical Accident Model and Processes (STAMP)**

One of the recent advances in the analysis of an accident model is the reference to the theory of systems. Related to this, the STAMP (Systems-Theoretic Accident Model and Processes) has been formulated by Levenson (2012) in his reference work: "Engineering a Safer World. Systems Thinking Applied to Safety".

This treatment considers that the accident appears from the interactions between the components of a system and do not derive from a single cause. The challenge in the use of the security analysis is to find out what went wrong with the operative of the systems or the developing of processes.

So in this model, the focus is set at the shortcomings, the lack of control and other dysfunctions of the system or its processes. The model is more sophisticated and very linked to the American aviation, where system la engineering is very developed.

## 2.5. The relevance of Bowtie Models: an Introduction

In this case, let us assume the danger we are analyzing is grounding (at a shoal at land).

Causes may be varied (this is the left side of the "bowtie"):

-   Bad visibility (that nowadays should not be a problem with the existent Electronic Aids)
-   Heavy waves or currents that hinder the ship's maneuver
-   Inadequate stowing of the cargo.
-   Altered state of the conning officer

    - Due to consumption of alcohol or drugs

    - Fatigue caused by excess of work or stress

-    Dysfunction of electronic aids aboard

    - Due to some dysfunction of the equipment aboard, error in design, etc…

    - Due to insufficient training of the coning officer.

And for each case we could design barriers that could be i.e.:

    - Proceed at safe speed as obliged by rule 6 of Collision Regulations.

    - Increase the power of the motors (that is not easy to do once the boat is afloat) or better, which seems more feasible: knowing the characteristics and capacity of our ship: avoid the zones where the meteorological forecasts are worse (in the case of a small boat, the option is to rest in port). Having the adequate towing boats is also fundamental.

Let us study now the right side of the Bowtie, the one of the consequences with its different branches.

If the bottom is soft (sand, clay) the consequences in theory must not be extremely serious. Maybe the ship will be capable of freeing itself with the tide, or it may need the help of tugs. In any case, it will be a blow to the professional career of the coning officer. Errors are expensive nowadays, since big ships cost a lot of money. In small ships, grounding may not have serious consequences.

If the bottom is rocky, a total loss of the ship may result (as in the case of Costa Concordia, e.g.). The environmental consequences may also be tragic (especially in the case of tankers). The barrier that was set is to design and enforce tankers with double hull.

The cost of the accident for the company must not be excessive especially if it was correctly insured. If there is any error or fissure at the contract it is possible to have heavy losses. Also there are international conventions to cover the cost of ecological disaster to a certain extent (e.g. FUND).

Another consequence would be the negative propaganda associated to the company. A barrier or method of solving this loss of credibility would be for example to invest in a publicity campaign. Misadventures may sometimes be exploited and in misadventure there are always heroic facts that may

be publicized (this would be the case of the Titanic orchestra and firemen: the firemen were pumping coal to the last moment, allowing for light and electricity on the ship till the last moment). Passage ships are maybe the most sensible to this negative publicity, but it may be observed that the cruising traffic and particularly that of the company "*Costa Crociere*", controlled by Carnival Corporation & PLC has been growing all the time, despite the disaster of Costa Concordia (2012). The case of the ferry "Herald of Free Enterprise" was more definitive (sunk 6 March, 1987) since the company Townsend Thoresen was bought ending 1987 by the Peninsular and Oriental Steam Navigation Company, changing its name to P&O.

## 2.6.-Final remarks about modeling accidents

As we have seen, we define the sequential linear model of an accident as a fail produced by a set of causes; amidst them the error in organization and at the systemic essentially as a defective control or a lack of control.

In the maritime ambit, most part of the commissions of investigation of maritime accidents continue using the sequential and epidemiologic methods described (US Coast Guard, MAIB, GNV-DNL, etc). However, it results necessary a transit to systemic models: electronics, interdependency of the ship and its Master with administrations, liner companies and other operators (DPA), and the growing complexity of the man-machine relation and its link with the systems/procedures, enable to forecast for an immediate future, the use of systemic methodologies, although this is simply to determine the primary cause of the accident, simply.

Within the systemic models, there are AcciMap, HFACS y STAMP: there are relevant differences, since they are instrumental techniques with singular methodologies that may lead to diverse results. In the complexity of our time, linear models are soon going to be obsolete to understand maritime accidents, at least in relation with the activity of transport. Resilience engineering has particular importance from the human perspective, since it studies systems where it is not easy that control is lost. In it, the error is the other facet of the necessary adaptations to face real-world complexity, and not an anomaly or dysfunction. The success is inculcated to the capacity of organizations, groups and individuals to antic to the changing forms that risk adopts before errors and the accident occurs. The fail occurs because of the lack, temporal or permanent, of that capacity. Security is something the system creates and thus is not an innate quality of the system. It is not sufficient that systems are reliable; they must also have the property of resilience understood as a capacity of recovering from dysfunctions. Obviously, it is a field of multidisciplinary knowledge where the instruments of analysis that we have mentioned are applicable, but that incorporates as very valuable the notes of adaptability and capacity of recovering of the systems (Rodrigo, 2015).

# Chapter 3: Trees of Events

## 3.1 Analysis by the tree of events

As explained at Chapter 1, this is a method of analysis to identify the cause of the accidents or adverse effects and its relations. It postulates the multi-causality and the implication of the human factor, but also and mainly the contribution of the system's flaws.

The base is always the Tree of Events and uses a reasoning logic that follows a path backwards in time from the accident to identify the malfunctioning and forward to find its consequences.

It is thus, a technique to investigate accidents based on the retrospective analysis of the causes. From the accident the sequence of causes that represent in graphical form the sequence of causes that have determined it.

The "near" causes may be divided in Obvious, Superficial and Immediate and the Subjacent Causes may be classified in

– Origin of near causes

– Remote

 –Subjacent or predisposing Factors

To construct a tree of events it is necessary to pick the information as soon as possible, at the place where theadverse effect occurred and by someone who knowsthe job. We will avoid judging, searching for culprits (or scapegoats) and we will interview all the persons, gathering the information on the conditions of work and the organization. Filling or producing the report it is necessary to differentiate between facts, interpretations and judgments (that aresubjective and personal opinions). Some authors construct the tree vertically, with the previous events on top.

When drawing the tree we must have very clear:

• Which is the last fact? (Adverse Effect, AE)

• What was necessary to produce this last fact?

 • Was any another fact necessary?

It will be built from left to right, so once finished it may be read chronologically.

• We may use these graphic codes:

Fact

Permanent Fact

Tie

Apparent tie
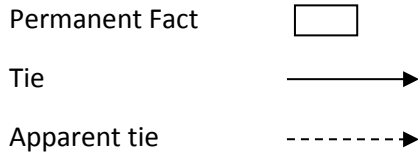
One time the tree has been drawn it must be exploited, with the aim of de limiting the future apparition ofthe accident orthe adverse effect:

Corrective measures may be devised that search to prevent in an immediate and direct way the causes that have caused the Adverse Effect or preventive generalizedmeasures for the whole of the situations and the organization.

The corrective measures must be applied to the most distant causes.

Potential Adverse Factors are those facts that without having caused the Adverse Effect that we are investigating could contribute to new Adverse Effects. They are followed and against them we will apply Preventive Generalized Measures (PGM)

Next we present the Systematic *Process of Retrospective Investigation of Adverse Results or Incidents* (sentinel happenings) in order to determine the subjacent factors that have contributed to its appearance.

The investigation is going to analyze the latent conditions (systems and processes, more than individual behavior). The aim is to identify and develop potential measures to diminish the probability that they occur in the future

To describe how the collection of information must be, we are going to answer to several questions:

When? As soon as possible (ASAP)

Where? At the place where the Adverse Effect occurred

By whom? By a person that knows well the work

How? Avoiding the search for scapegoats and being objective and exhaustive with the interviews, interviewing all the people and gathering information on the work conditions and of the organization.

While writing a report, we must differentiate between facts, interpretations and judgments. They are next defined:

Facts: Objective data that describe a situation. Example:The modern practice of registering ships at foreign countries was originated at the United States at the time of the First World War.

Interpretations: Explicative information insufficiently elaborated. Example: The reasons to choose a Flag of Convenience (FoC) are varied and include reducing the taxes, relaxing the conventions and national treaties on work or environment and the greater facility to contract crews from less developed countries.

Judgments: Personal and subjective opinions. Example: The labor conditions are intolerable at many ships with Flag of Convenience.

Once everything is pretty clear and written, we may create (draw)the tree: in order to do that we must have answered:

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- Which is the last occurrence?
- What was necessary to produce this last occurrence?
- Was another occurrence necessary?

Then we must differentiate between:

**Chain:** To produce fact (A) it is enough with (B)occurring, but it is not necessary. So by simple logic we may deduce that if *(A) does not occur, then (B) cannot be*.

$$(B) \longrightarrow (A)$$

*Example*: If the sling breaks, the load will displace. B would be the broken sling and A the displacement of the load.

**Conjunction**: To produce (A) two causes are necessary, (B) and (C), none of them is sufficient and also they are independent between them. Statistical independence is very easy to define: two facts are independent if the probability of both occurring is the product of the probability of each one occurring.

(A) ⎤
    ⎥→ (C)
(B) ⎦
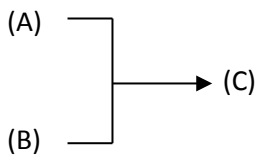
Example: The fire (C) started because someone threw a light cigarette to the garbage (A), and the garbage was full of rags soaked in oil (B).

A typical case is the breaking out of a fire: as presented in Kristiansen (2005) three factors must be present: a combustible material present (solid, liquid or gas), oxygen and finally a heat of ignition source.

**Disjunction:** Two facts have a same cause (C). (C) is necessary and sufficient to produce (A) and (B):

Example: When the fire in the garage starts (C), a blasting alarm is instantly triggered (A) and also automatically the sprinklers start pouring water (B).

      ⎡→ (A)
(C) ──⎥
      ⎣→ (B)
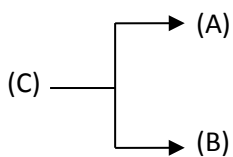
Once we have been able to draw all the Event Tree, we would go on to the Third Phase: the exploitation of the Event Tree.

So we must apply the corrective measures to the farthest causes. If we act on thefarthest, we prevent the entire branch. However, we must differentiate between 2 classes of measures:

• Corrective Measures: are the immediate preventive measures that must be applied to the Adverse Effect (AE).

• Potential Factors of AE: fact that may cause AE in other occasions, potentially, and that we formulate from the AEthat we are investigating. So, it could be an indirect causeof our case.

# 3.2. Root Cause Analysis, RCA

So, in order to find all the possible causes in an Adverse Effect, we are going to study the causes of the fail by another method: the Root Cause Analysis or RCA.

Is this a systematic process of retrospective investigation of adverse results or incidents (sentinel occurrences) in order to determine the subjacent factors that have contributed to its existence. It is centered in the analysis of the latent conditions (systems and processes, more than individual behaviors). The aim is to identify and develop potential enhancements to decreasethe probability that they occur in the future.

So we must study in detail the process that has carried the adverse result. For this we must differentiate between Sentinel Events, which are adverse effects and Incidents "near misses" where theadverseresult has not occurred simply by chance. Evidently, these seconds will be more complex to study since the impliedpersons will probably try to minimize or keep silence over the problem, although this depends on many factors. In general, the affected persons will try that the "near miss" will not happen again, although they probably will not leave any register.

So, we must focus the process that has the adverse result (or the incident).

• What happened? The facts must be described.

• How did this happen? In this case, the focus is set on the Process.

• Why did it happen? The causes are studied

• May it be avoided at the future? In this case the formative measures and prevention instruments are crucial (so a cultural change takes place, in order to enhance security).

We must ask ourselves if the person or persons in charge of carrying out this study (of the Fault Tree and the causes) are the adequate. If we assume that it is a complex study we must assume that it is a multidisciplinary team. Really, any work that is worthwhile must have at least two persons so one may retro-feed, check, and contrast the work of the other. Well, a lot has been written about the organization of work (and it has been compiled in the ISO).

At the top we may find the Leader/responsible, that must be animplicated and motivated individual, familiar with the process, beyond his academic formation.

Under him or her we may find the Consultants (or Advisors). It is important that they are interdisciplinary: they must be experts in their field and be prone to teamwork. They must have illusion and vision of a better future,

To write a report in depth, rigor and credibility it is necessary in first place "Method", that may be obtained with own experience or basing on other similar previous studies. However, it is also possible to write a report from blank, dedicating more time to the detailed study of the system.

**Features of a report**

A report must in first place have clarity and precision. The "why" of every pair cause-effect must be studied exhaustively, in order to know if the effect was inevitable or there was a probability it did not take place. This may lead to complex mathematical formulations.

The report must be consistent (this is, there must not exist any logical contradiction).

The existent evidence must have been revised exhaustively. The occurrences in time must be well framed (in space-time). It must be objective, since the aim of the study is not to find culprits but to ameliorate the process. The current aim of industrial processes is to fulfill the objectives in a culture of improvement and safety.

El report must finally be useful. Changes must be Identified and proposed, since if we do not propose enhancements surely we will not be hired for another report. A plan of enhancement must be then proposed.

**Phases of a RCA**

These phases could be used as an index at a report.

1. Inthe first place the problem must be identified (brief description of the process)

2. Define the team and the Consultants

3. Analysis: What happened exactly? It is necessary to carry a compilation of information in orderto find the near and subjacent causes (map of the facts). Confirmation of the causes (by the consultants)

4. Explore and identify the strategies of risk reduction (study of barriers)

5. Make recommendations (solutions, plan of action)

6. Report. The human factor will be considered and possible changes of behavior.

To analyze the process interviews must be done to find the facts and causes. Also, it is necessary to search data, mainly protocols, norms, regulations, documents of maintenance (all in the company) and naturally, it is also necessary to carry an inspection *in situ*, revising resources,  etc...

## Example:

*Let us assume the investigation of a machine that has stalled since it got overcharged and the fuse broke. The investigation shows the machine has overcharged since a bearing was not sufficiently lubricated. The investigation goes on and we find that the mechanism of automatic lubrication was formed by a pump that did not pump enough; thus the lack of lubrication. The study of the pump shows a wearied-out axe. The investigation on why the axis was wearied uncovered that there does not exist a mechanism to avoid the metal scraps from getting the pump (reaching its axis). So, a scrap of metal harmed the pump. The root cause of the problem is then that the iron scraps may contaminate the lubrication system. Fixing this problem all the sequence is avoided. This well-carried investigation must be confronted to another that does not find the root cause: changing the fuse, the bearing or the lubrication pump will enable the machine to work for a while. But there is the risk of the problem occurring again, if the Root Cause is not solved.*

There exist several sentinel facts in the maritime ambit susceptible of being studied by the RCA method: accidents and breakdowns must be the most important, although also pretty different topics may also be studied such as diseases (medical diagnose).

Las Root Causes may be very diverse:

• Errors in communication:

• Errors in Focusing/training

• Insufficient information at hand

• Inadequate organizational structure/culture

• Standardization /protocols obsolete

• Changing and Adverse Environment

The report must be very rigorous with the causal reasoning.

The logic cause-effect must always be remarked (Rules of the causal inference). Also, it is recommended to avoid these negative terms in the human behavior: error, neglect, carelessness... It must be considered that every human error has a cause that precedes it. This is, every deviation of the system (breach or non-compliance of norms, good practices, etc…) has an anterior cause. An error is thus the cause of an effect only if there existsa previous and clear obligation of acting.

Hence, it must be studied where to "scratch" in order to produce the report. In this case the work must have some resemblance to a police investigation.

A field to study is the **Communication** (between the affected). Certainly, the work environment or atmosphere and the human relations have a fundamental role in human errors. Hence, the following must be explored:

– Personal and professional relations

– Information fluxes

– Availability of information

– Politics and informative culture (how the information is shared, existence of barriers, etc)

Another field to consider is the **Formation and Capacity** of the affected. The lack of supervision, experience, formal education, etc...

Also, the **Work** must be studied as an end in itself: fatigue, turns of work, stress that is the cause of distractions.

Relatingthe equipment and resources, it must be considered if the Design is error-proof, which safety controls are there, specifications and instructions and its disposability, the actualization of equipment, etc...

RCA may be hailed as a menace in several cultures and ambiences. A change of culture always finds resistance. In these cases, we must work giving constant support to the management of RCA to attain success, and also using non-punitive policies when finding problems.

RCA is used typically as a reactive method to identify facts, reveal problems and fix them. Analysis is done *after* the event has occurred. However, some features of RCA make it useful as a preventive method. Thus, RCA may be used to prevent *or predict* probable events *before they* occur.

**Analysis of the tree of events or consequences**

This is the study the consequences caused by the accident (or adverse effect, AE). It must be noted that the AE could be considered a cause of a new AE, the consequence. So the AE would be a new one

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forward in time. However, as accident we will choose always the most elegant "knot" of the problem (that is, the center or knot at the Bowtie model).

## 3.3.Numerical Analysis of the Tree of Events

Root Cause Analysis is usually applied at industrial processes where the probability of an event can be calculated or at least approximated to some degree. In this way, the probability of the accident occurring may be calculated by the simple rules of combination of probabilities, for each branch. If the branches are independent, then the final probability is the sum of the probability of the different branches. It must be remembered that probability (statistics) is a branch of mathematics and thus, once the postulates are set, there is nothing to discuss since the derivations follow as logical conclusions (the postulates may be discussed, evidently).

Statistics defines de probability of an event A, *P(A)* as the limit (if it exists):

*P(A)*=(number of "favorable" cases)/(number of total cases)

It is thus a number between 0 and 1 (both included). If we obtain any other number, there is an error at some place. In statistics everything is invented (at least at a useful level for us) and thus the only problem is to find the appropriate formula.

In a maritime or shipping accident, a probability may not be calculated, since the probability of an event is defined as a limit, when the number of total cases tends to infinity. The number of cases may be assimilated to the number of experiments that may be carried. The problem usually is that we cannot carry as many experiments as we want (as we may tossing a coin). In the case of maritime disasters we may only wait and observe the events. Then, the problem that appears is that as time goes on, the experiment changes since the environment changes. If we study maritime accidents ships are different, and also the formation of the crews, and even the environment changes.

It is true that sometimes it is not necessary to reach very big numbers, if the probability is not very high or low. To assess very improbable events, we must carry many experiments (so it is difficult to assess probabilities of great accidents since there are not many).

The standard deviation, σ, of the estimation (or estimator) of *P(A)* is:

$$\sigma = (P(A)\cdot[1-P(A)]/N)^{0,5}$$

N is the number of experiments. This is explained at academic books about statistics at college level. The demonstration is based on the binomial distribution (where there are only two results: favorable or unfavorable). For a considerable number of cases or experiments, N, the distribution is similar to the normal distribution and thus we have 68.2% of probability, approximately, that the real value is between *P(A)*-σ and *P(A)*+σ. The importance of this is that normally it is not very important if the probability of an event is 0,5 or 0,505 but it may be important if it is 0,0001 or 0,0051 (the absolute difference is the same). Thus the difficulty of estimating the probability of improbable events that usually is at the tail of continuous distributions (extraordinary tempests or waves, peak events in general).

There are some distribution functions that have been designed especially to model peaks or improbable events. These are the extreme distributions (for maximums and minimums), that may be reduced to 3

types, depending of the behavior of the tail and its growth. It has been shown (e.g., Vergés, 1995) that the different methods of fitting the three or even more different distributions result in a great variance of the extreme results that are interesting for damage analysis. Thus, it is concluded that we must not rely only on the statistical results (which are only numbers) but also consider the economic variables of the damage to minimize the risk of the damage (this is $ or €). In this way, we may minimize the expected generalized economic loss caused by this specific event. Evidently, this is easier to write than to do.

Another totally different approach that may be used to calculate a probability that is "*a priori*" difficult to estimate is the Bayes' Theorem. In it, there exist estimations a priori of certain variables that may be contrasted as we obtain more information on the problem, obtaining thus a probability "*a posteriori*". At the Appendix 1 is presented a more detailed explanation and a practical case.

## 3.4. Examples

As an example we can set is the well known case of the Titanic: the most studied shipwreck in history, and that although it was not the one that caused more victims, it haunted the imagination of several generations. The information for this

We are not going to enter in details about the shipwreck that has been exhaustively studied (Luis Jar Torre,). In most cases the studies insist that there was real bad luck, in statistics this could be described as a "Black Swan", something that nobody believes possible but occurs (it really is not so difficult for a Black Swan to exist since there is a species named like this, not in danger). An example of a black swan is the failure of the Fukushima nuclear station due to the 2011 tsunami.

Maybe the worst fatality is the way in which the hull of the ship was ripped by the iceberg. It is true that the quality of the steel at the time was not the same as today but fatality wanted that the loss of water tightness affected 5 consecutive compartments at the prow, while with 4 it might have survived. The waterovertopped the compartments as the prow sank deeper and deeper, condemning the ship.

Next we present a tentative tree of events of the accident (and since it is not a typical accident, it is not a typical tree of events).

It must be remarked that the tree of events is only to the moment of the collision with the iceberg. It is evident that more lives could have been saved if Titanic had carried more lifeboats and if its crew was more trained. How many lives, we do not know but we do not enter in this problem that has been exhaustively studied, like everything related to the Titanic.

In order to begin with the study of the Titanic I have used the "Story of the Wreck of the Titanic", the original account published in 1912 by Marshall Everett in the immediate aftermath of the tragedy (using the information of the trials), reedited in 1998 by Conway Maritime Press. Also, since to collect all the literature on this subject is a vain effort, I have used an article by Jar Torre (1998)[3], titled "*Los Tres*

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[3]Los Tres Titanes gafados. Revista general de la Marina. May 1998.

*Titanes Gafados*" which in Spanish means "*The Three Unlucky Titans*". It deals mainly with the Titanic (although it also explains the story of the *RMS Olympic* and *HMSM Britannic*) and offers an abstract of the tragedy concentrating in the crew..

(http://www.grijalvo.com/Batracius/Batracius_Titanic.htm). This author, an authority in the Titanic, has also an article on the SS Californian ("*La nochemásnegradelCapitán Lord*", the Blackest Night of Captain Lord), who failed to rescue passengers from the Titanic (its radio was not working 24 h a day) but we will not consider this in our analysis

**Titanic:**

The biggest ship in the world at its time (tied with her "twin sister", Olympic, who was the first of a series of three). Not the fastest ship at the time.

It was the proposal of the White Star Line to compete with the Cunard. Luxuries and all the modern technologies: electricity to close the water tight doors, telephone between the bridge and the lookouts at the watch.

Materials: the steel at the time was not as strong as it is nowadays. But it was OK for the time, when there were no quality controls as nowadays.

**Maiden voyage:**

Captain Smith had participated at the sea trials of the Olympic,

Near collision with the moored SS City of New York at the port of Southampton due to hull-hull interaction (missed for some 1,2 m). This shows that naval science was not as developed as nowadays at the time, especially dynamic effects of large ships.

**Captain Edward Smith:**

It was his last voyage since he was going to retire after it. Excess of confidence?

Conditioned by the presence of his ultimate boss, Mr. Bruce Ismay aboard?

Conditioned by having to play social life (he was known as the captain of the millionaires)?

**Radio operators**:

The radio was telegraphy (slow).

The business in these cruises was the communication of the passengers with land (where the money was).

Titanic was warned of ice field by SS Californian.

**Weather:**

It was an unusual spring with icebergs way south. The rest was OK.

A report of icebergs did not arrive to the bridge (the Captain and Mr. Ismay) kept

**The lookouts:**

There were two of them (although according to the regulations with one it would be enough)

They were not relaxed since they were advised to look especially for icebergs.

They found there had no binoculars at the bridge they made a note to get some at New-York.

Unfortunately, there were no waves and then there was no foam at the flotation line of the iceberg.

**The maneuver**:

The maneuver has been sometimes criticized by some experts.

However, according to the last investigations (Jar, 20), the most probable is that the collision with the iceberg was inevitable.

What may not be discussed is that the Officer did his best, and that without further training and experience with the ship he could not have known the optimal way to clear the obstacle.

The fatality was then that the ship almost cleared the iceberg: had the collision been frontal very probably she would have survived

**Figure 17**: Tentative and simplified tree of events for the sinking of the Titanic (1912)

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Now we arrive to the difficult part of the analysis, since we aim to do something original: give numerical values and connect the different events in the tree. It is true that ships had been crossing the Atlantic during many years without major problems. It was in many aspects "the first time". Before 1912 there had been many tragedies in navigation but it seems that only one with more victims. Curiously, the two greatest disasters before the Titanic were 2 similar sidewheel steamships (Mississippi type) whose at the USA (*Sultana*, in 1865, with 1,800 deaths out of 2,427 passengers and *SS General Slocum*, in 1904, who took fire is second with more than 1,000 lives lost out of 1,400 persons aboard).

First of all, we must introduce at the analysis the fact that it was the maiden voyage. Evidently, the first time is more difficult. More attention is put, true, but this may not compensate the knowledge that gives having carried something out several times.

Another factor that traditionally has been set forward is the presence of Mr. Bruce Ismay, the CEO of White Star, on the ship. Did it condition, in some way, the behavior of the Master, Capt. Smith? He was an experienced seaman, true, but the presence of one's boss is always something to consider.

Maybe the most statistically analyzable number is the probability of an iceberg being in the route of the ship. For this we must know if the distribution of icebergs at that latitude was random, their size and how many were there (in mean, every hectare). Statistically, nothing else is necessary. Some ships (such as SS Californian) stopped to pass the night (due to the ice field). In this work we do not have the time (or means) to investigate this particular problem, but since we have vowed to give a number, let us assume it is 0.5. Maybe high, but it was a most peculiar night according to all the records.

Once the iceberg is in the route of the ship we must consider the probability of clearing it, crashing not fatally with it or crashing fatally, as happened. The important probability for our study is the last, and it is not easy to estimate. This is the probability that is really the key of the problem. The probability of the lookouts having or not the binoculars, etc, may perhaps be calculated but this would be only an input to this hazardous estimation. We will assume for academic purposes that this is 1/400 (=0.0025, this is, that in 400 collisions with an iceberg, a ship as the Titanic, with its flaws but undoubtedly seaworthy, would be condemned. Maybe it is a little low, but we may not carry the experiment many times…in theory we could, but it would be, very, very expensive). Making a simple search, we find that very few ships have sunk due to a collision with an iceberg, so it must not be very probable.

In this case, the estimation is very simple: the probability of the foundering of the Titanic (at a voyage at a time of the year where icebergs are common) is then 0.5·0.0025=0.00125. We must finally consider in some way the factor of the maiden voyage and the fact that Mr.Ismay was aboard. This is always difficult, but well, we must consider (in a non-standard way) that each fact may double the probability of an accident. Then the final probability would be 0.00125x4=0.005. This is a pretty high probability, 1 every 200 trips (a round number). We may also consider that the presence of Mr.Ismay had not any effect, then the probability would have been 0.0025 (1 every 400 trips). The same happens if we consider the effect of the maiden voyage negligible.

What is indubitable is that the foundering of the Titanic was a "glorious wreck", exemplified by its orchestra that played to the last moment and the heroic firemen that shoveled coal to the engines until they were washed away.

I do not pretend to contribute in some way to the Titanic discussion in this work but only present an example. Finally, not all the consequences of the wreck have been negative. For instance, books have been written and several films have provided work, entertainment and income to many people.The search for the Titanic has boosted in general underwater investigation, with the breakthrough of Ballard in 1986, who found the wreck. The recovery of objects has also boosted scientific innovation and they have been auctioned and shown at expositions.

The legacy of the disaster is also the First International Convention of Safety of Life at Seas (SOLAS), in 1914, which did not enter to effect immediately due to the First World War.

In another example, we are going to study the consequences caused by less tragic accidents (or adverse effects, AE). It must be noted that AE could be considered a cause of new AE, other consequences. So there would be another AE (more forward in time). However, as we will choose as the accident the most elegant "knot" of the problem (this is, the center or knot at the Bowtie model).

Thus, we are going to present a first example of a complete tree: we will try to present a case based in agriculture that may have a great economic importance. Fruit transport has evolved a lot since the times of the neo-colonial Fruit Companies of the eighteenth century and now it is a science.It must be noted that the tree model is indicative and thus it might not bear any resemblance to the actual situation, but it may be useful as a mental model, or a situation to attain.

In this case we will not try to estimate values for the different branches. We present this example to show that it is maybe possible to make some reverse analysis: this is, if we know the probability of some container loaded with fruit to be rotten, we may track down the different probabilities and thus which branches we must concentrate to "cut down". We must consider that to "cut" or eliminate a branch has an economic cost (and also uncertainty) but we may conclude that it is worth the effort.
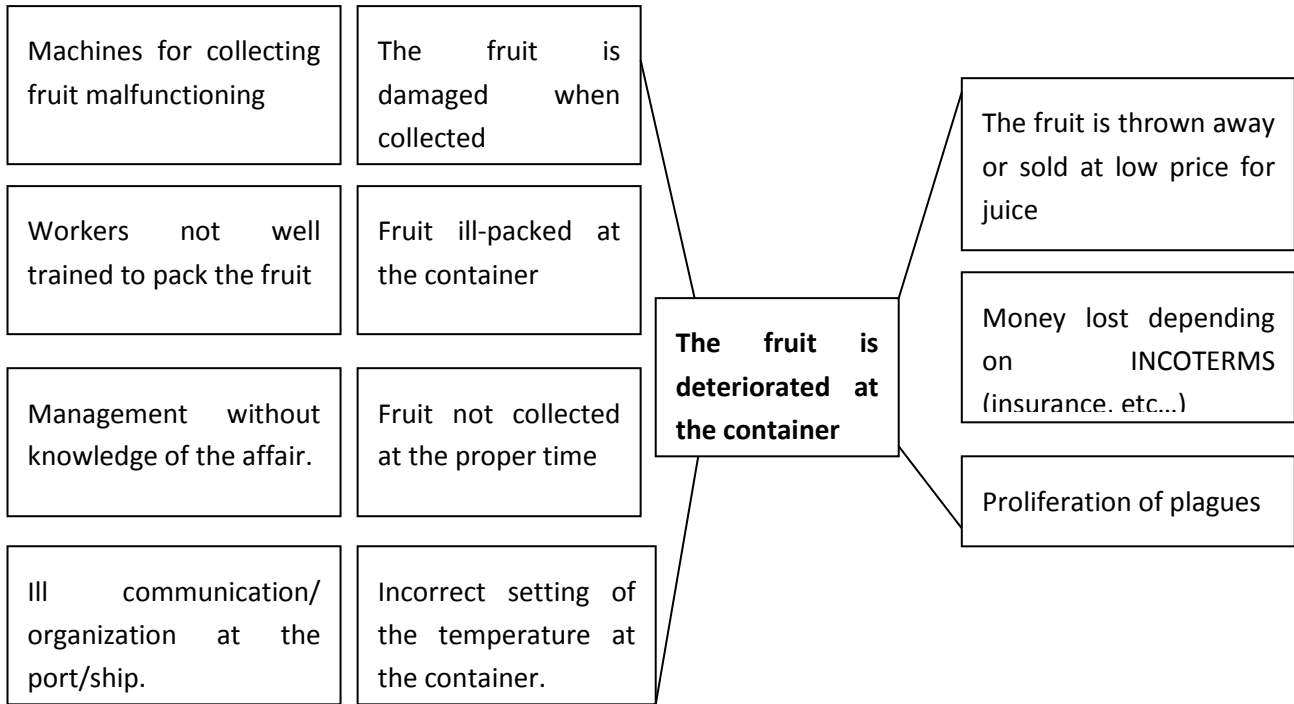
**Figure 18**: Bowtie model of fruit deteriorating at a container.

Legacy: First International Convention of Safety of Life at Seas (SOLAS)

# 4.General Bowtie Model for Maritime Accidents

So once we have made an introduction of the different methods of analyzing the fails (the accidents) and the probability theory we are in a good disposition to try and set a general analysis of a bowtie model for maritime accidents. Finally we have decided to make a general model since the world of maritime is changing so quickly that trying to concentrate on a single cause may

According to Gates (1989), after reviewing the initial facts regarding a maritime casualty, one can make certain guiding assumptions which, while not eliminating all the wrong possibilities, will direct the investigation towards the most likely cause of the casualty. One can start by looking at the weather. Did the casualty occur during a clear day with visibility and not extraordinary waves nor wind? Then it is very probable that the environment did not play a major role in the incident.

Navigation and communication devices must also be chequed. In this case they were checked and found to be in good working condition prior to getting under way. It is improbable then that either navigation devices or communications were involved.

Next, one might take a look at the control of the vessels. Is the speed of the ship above steerage? Was it excessive? Also, we are always thinking on navigation at open waters but if the casualty occurs at a waterway, it must also be studied: was it wide, did it have bends, what was the velocity of the flow? As water flows around a bend, the velocity flow increases at the outside of the bend, causing erosion, and decreases at the interior, which in turn causes deposition.

Next we present Bowtie model with the tree of events (at the left)that is very general, tentatively. It is true that without entering in details an accident may be caused by a human error, a natural hasard or a technical failure. It may also be a combination but there will be one main cause. We have included the case of piracy/terrorism because even though they are not "accidents", they have helped to design strategies to prevent these attacks, barriers.

The tree of consequences is at the right, and really the consequences are also simple: there may be environmental and economical damage, reputation lost and loss of human life (which is the more irreparable but not the more costly, usually).

So at the next figure we present a general Bowtie model for maritime accidents, hoping it helps to settle the hypothesis that cause accidents.

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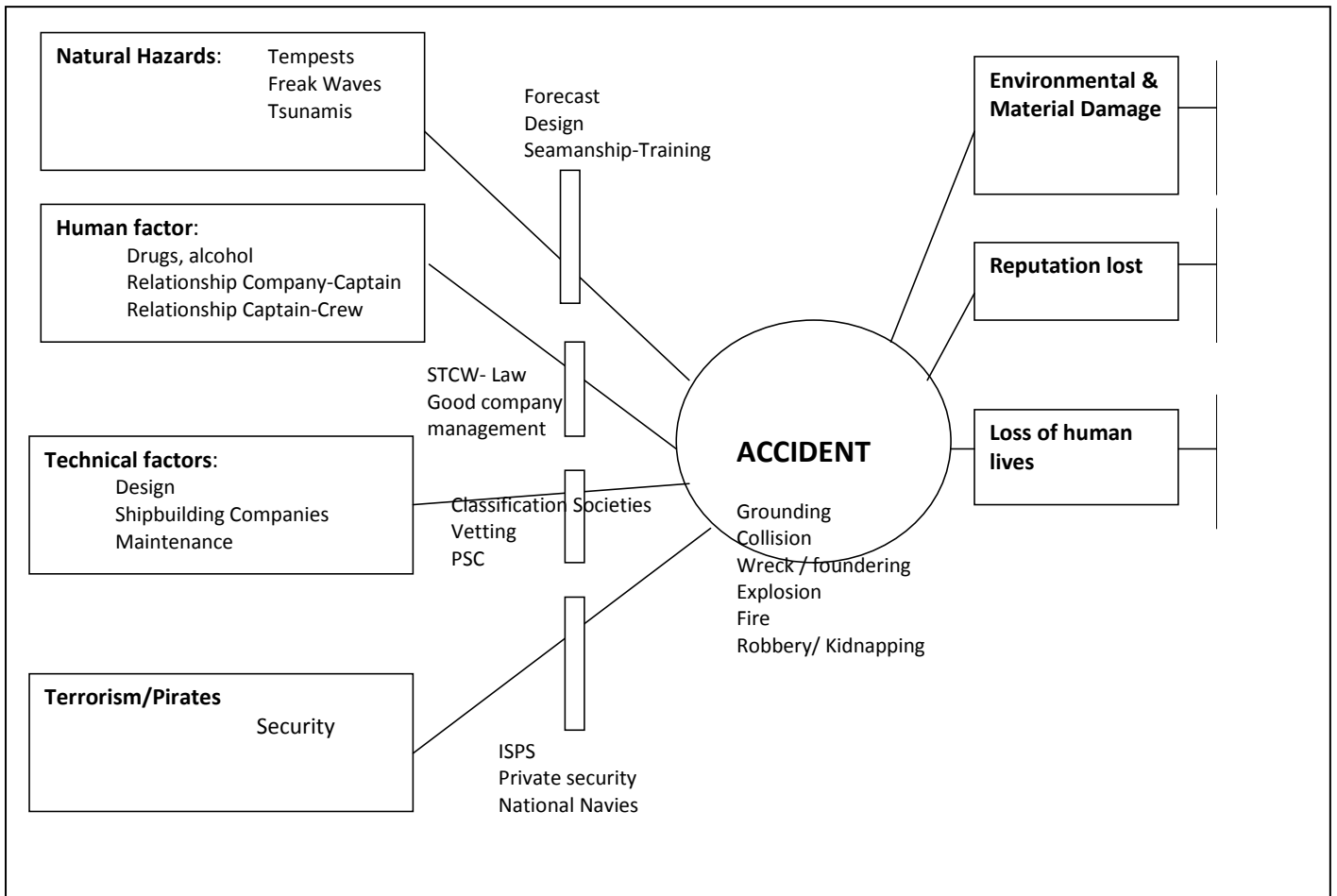
**Figure 19:** General Bowtie Model (Causes of an Accident and its Consequences). The possible barriers are represented to prevent the Accident. Once the accident has occurred, some authors put new barriers before the consequences, but I have preferred to put the barriers at the far right, without detailing. These are the measures to mitigate the damage (to reduce or eventually eliminate the loss of human lifes, for example).

Once the accident has taken place, there are many ways to mitigate the situation that usually need an intensive use of money. We will showsome way to mitigate the undesirable effects but we will not enter in detail so the aim of Error Analysis is to prevent the accident.

# 4.1.Natural hazards

At sea the most important hazard are usually sea waves, sometimes associated with strong winds (hurricanes) that although they do not have the same danger and importance as in the times of sailing they can still pose a problem for the stability of the ship. The wind may be considerable mainly at ships with great surface over the water like cruising ships, but not at ships like tankers usually whose main surface is underwater (and besides, when they are loaded its overall density is much higher than in the cause of cruising ships: these two cases are almost opposite in what concerns the response to the wind). It is true that the strong winds associated with overtopping and rushing water over the deck of the ships may cause severe harm (broken windows, hatches, containers lost) but usually they do not cause the sinking of the ship (although sometimes it may cause the ship to become derelict and thus to require help).

### 4.1.1. Storms

However, the main danger that actually may cause the sinking of the ship is the hydrodynamic forces of the water waves (it must be remembered that the density of water is almost 1000 times greater than that of air -1025 $kg/m^3$ against 1.225 $kg/m^3$-. This was surely the case of the Derbyshire sunken by a typhoon in the waters of the Sea of Japan, the Fitzgerald, the greatest carrier sunk at the Great Lakes (which demonstrates that the wind may cause high ways and thus dangerous conditions once in a while at those lakes) and, in more recent times, the deeply studied case of the Prestige, sunk off the Spanish Coast of Galicia (Finisterre or Ends land). This is also the last case, to this day, of a big ship sunk by causes that are technical and natural, without the captain or the crew having committed any navigating error (it may be discussed if the captain should have refused to sail, or if he didn't accept at first chance the "help" of the tug, but all this problems have been exhaustively studied in a 10-year trial and a public coverage. It is still a very sensible case, politically and socially where at last it seems the only scapegoat is as usual the person with less power, Captain ApostolosMangouras, who was near to retiring due to his age (see, e.g. Zamora, 2013[4]).

The way to navigate through big waves to avoid excessive heeling and worse dangers is usually to put prow to the waves and reduce the speed to the minimum steering speed (in some films which usually try to mimic reality although making it more "spectacular", e.g. "The Perfect Storm" to ride the gigantic waves the ship sets its maximum speed to "pass" each wave, but this is the case of small fishing vessels (L≈15 m) that may vary the regime of their motor easily. Another maneuver may be to put poop (or stern) to the waves and also adequate the speed to have always the possibility to maneuver. The speed must not be high to avoid "surfing the waves", thus losing control (which in the case of smaller waves could be a fine way to gain velocity "riding the wave").

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[4]http://www.naucher.com/es/actualidad/la-sentencia-del-prestige-prueba-de-cargo-contra-la-criminalizacion-de-los-marinos/_n:1361/. The maritime community of Catalonia has offered his support to Capt. Mangouras. The efforts of the Spanish State to sue ABS, the Classification Company that had certified the ship had have proven unsuccessful.

Normally in all the studies of sea states (for example, the Douglas scale) the most important factor is the wave height, expressed as significant wave height, Hs, which is the mean of the highest third part of the waves (or In other words, the mean of the waves higher than the percentile 66,6%). The state of the sea must be thus defined over a period of time, usually 10 or 15 m. During the tempest, the state of the sea may be registered (by automatic buoys, etc, since the visual estimations from seafarers may never be exact), every hour or every three hours, for example. Thus we have the peak of the storm. The buoys usually do not record the height of individual waves (which is the difference in meters between the sine and the crest, considering the beginning of each wave the ascendant crossing of the Mean Water Level (MWL). Of course, the height of each individual wave would be a little different if we considered the beginning of each wave the descending crossing of the MWL, but we may assume that its statistical properties, and thus the significant wave height, Hs, will remain the same. What the buoys usually record via accelerometers is the acceleration and thus the energy of the water at the site. This energy is proportional to the square of the wave height in regular waves (the waves that are all equal, as may be created at a flume) and thus to the quadratic mean of irregular waves. From the quadratic mean wave height, the significant wave height may be obtained.

$$E = \frac{1}{8}\rho g H_{rms}^2 \tag{1}$$

$$H_s \cong \sqrt{2} H_{rms} \tag{2}$$

What is important and the point of this, is that two sea states may be significantly different and yet have the same Significant Wave Height. For instance, the direction of the waves may be very different, very focused, as in the case of swell waves or coming from different directions (disordered) as in the case of the waves that may be found at the "eye of the hurricane". The directionality of the waves may also be described by more complex (and expensive) buoys. Finally, the third important first-order parameter of the waves is the period (besides the direction and Hs). The peak period is that which contains the maximum energy at irregular waves (at regular waves it is directly the time between the recordings at one point of two consecutive crests or troughs). The period of the waves is very important because it gives the length of the water wave. In deep water, which is always at the middle of the ocean for wind waves, the relation is:

$$L = gT^2/2\pi \tag{3}$$

The deep water hypothesis (that means that the movement caused by the waves at the bottom is negligible) may be applied when the depth h is greater than L/2. So for a period of 8 s the wave will have a length of some 100 m (assuming deep water, h>50 m: with decreasing depth the waves shorten, shoal, and finally break. Not a single commercial ship is designed to navigate between breaking waves, since the forces and velocities implied are greater and more persistent than in the case of nonbreaking waves. There are different modes of breaking waves and there is plenty literature about the topic but it must be considered that commercial ports are designed so the waves never break at its entrance and if for any reason waves should break (because of an extraordinary storm or bad dredging) the entering the sheltered waters of the port should be delayed till the situation is over. For mild-sloping bottoms such as beaches, a good criterion for determining whether a wave is breaking is an old empirical formula from 1894 by McCowan that experimental measurements by Hardisty and Laver (1989) have found exact within +/-5 m of a barred beach profile.

The formula for determining the point of wave breaking is where the relation of the wave height H (considered an individual wave to the depth h is equal to 0.78. So if H<0,78h the wave is broken and the navigation Is thus dangerous (although good seamanship and design of the boats may allow the ship to succeed crossing a shoal with breaking waves).

Thus, assuming the wave is not breaking, if the length of the wave is big (having a big period T), the danger caused by the wave is scarce (because the wave is not very steep and the boat will rise and sink - the heaving movement- slowly, even if the wave is high). The problems may appear when the wave shortens, to the point that it has the same length as the boat so if the boat navigates perpendicular to the wave fronts the ship hull and keel will suffer alternatively sagging (with wave crests at the ends of the ship) and hogging (with a crest amidships). This force after many cycles may cause a failure of the ship by fatigue, causing the cracking of the structure after many cycles even though the maximum stress within a cycle is well within the resistance of the steel of the hull. This may have been the case of the *Flying Enterprise*, a Liberty Ship (thus built quickly) sold in 1947. The case haunted the imagination of the maritime community the Christmas of 1951. The ship left Hamburg bound for the USA (21-12-1951), but she encountered a storm in the Western Approaches to the English Channel. She suffered structural damage and a crack appeared (perpendicular to the fore-and-aft line) across the weather deck. The cargo also shifted and the ship listed 45º to port. The crew and passengers were evacuated with the loss of one life, but Captain Carlsen remained on board to direct the salvage efforts, that were carried by several tugs. Finally the ship broke in two the 10-1-1952 and sank just 41 nm from Falmouth, Cornwall, with the exhausted captain and an officer from the tug jumping to the water to be rescued.

This discussion may also be applicable to the case of the Prestige, which suffered damage at one side, at one of its 12 tanks, on November 13, 2002 before being battered by thousands of waves during several journeys and finally breaking in two. The discussion at the Prestige is whether the first damage was caused by stress or either by a **freak wave**. Surely the storm at the Galician coast was considerable but the ship had been designed (and certified by ABS Classification Society) to resist waves that high.

However, in our days weather forecasts are each time better and more accessible. Most ships do not have to use "rules of thumb" to avoid storms, but many companies now they have a "router" that designs the best route to be followed by the ships. The ships also receive the weather reports via NAVTEX, radio bulletins or may download forecasts from Internet In this way, accidents of great ships have drastically diminished in the last years. However, small ships, usually fishing ships sometimes are trapped or are forced to go out in bad weather and succumb to the elements. It is a fact that since the Prestige disaster in 2002 no other tanker has foundered. There has been a major oil spill, Hebei Spirit, at South Korea in 2007, when some 11,000 tons of crude oil where spilled causing an ecological disaster. but it was caused by a barge that was being towed hitting the tanker, that was at anchor, near the touristic beaches . The barge was floating free after the cable linking it to the tug snapped in the rough seas. The tanker was repaired quickly to prevent further crude spill. It seems a disaster that could be prevented, but as always, if nothing had happened nobody would have been concerned.

According to the Mariner's Handbook (2004), the development of weather routeing has followed advances in the collection of oceanographical and meteorological data, improved forecasting techniques and international co-operation, the introduction of orbital weather satellites and better communications. Weather routeing makes use of the actual weather and the forecast weather in the vicinity of the anticipated route. The routeing may be satisfactorily carried out on board or use can be

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made of one of the weather routeing services provided by certain governments and consultancy firms. The British Metorological Office, Exeter, provides a routeing service for ships worldwide.

What is a fact is that the number of major oil spills has been cut down (from 8 between the years 1988-1993 included to only three between the years 1996-2007. For the first time in the history of the existence of supertankers, we are heading to a decade without major disasters although there are always minor accidents and the guard cannot be lowered.

### 4.1.2. Freak waves

Freak waves or rogue waves, also known as monster waves, killer waves or extreme waves are large and spontaneous surface waves that occur far out in ocean water, and can be extremely dangerous, even to large ships and ocean liners. In oceanography, rogue waves are more precisely defined as waves whose height is more than twice the significant wave height. Therefore, rogue waves are not necessarily the biggest waves found in the sea, they are unusually large waves found in a sea state. Most seamen claim to have seen at least one, and I (not a seafarer) believe I saw once one of these waves, kayaking around the island of Minorca, at the Mediterranean Sea. It was at the south of the island, abandoning a little sandy bay…the waves were maybe Hs half a meter, although this is always hard to estimate. Suddenly I felt the sea stood still and for some moment and at the distance I saw a wave forming, swelling…that would be ideal for surfers, but I was kayaking (kayaks may also surf a wave but that was not my idea). I accelerated and cut the wave (not perpendicularly but with an angle). The wave was pretty vertical and at least a meter high (thus, a Rogue wave) and it shook my kayak, sending the prow up. After the wave, everything was calm again, and I watched the wave approach the beach visibly and break. A rogue wave is also featured at the film "A Perfect Storm", not the final wave that sinks the ship, but near the beginning of the film, at a calm sea, a wave maybe 1 m high that shakes the ship and causes certain distress to the crew.

Freak waves seem not to have a single distinct cause, but occur where physical factors such as high waves or strong currents cause waves to merge.

Rogue waves may also occur in lakes. A phenomenon known as the "Three Sisters" is said to occur in Lake Superior when a series of three large waves forms. The second wave hits the ship deck's deck before the first wave clears. The third incoming wave adds to the accumulated backwashes and suddenly overloads the ship deck with tons of water. It must be considered that in this case three gigantic waves affect the calculation of Hs (the mean of the third highest waves over a period of 10 or 15 minutes), increasing it, so it is difficult to consider that three consecutive waves may be freak waves (although they may be 1,5Hs, for example).

The loss of the MS München in 1978 provided some of the first physical evidence of the existence of freak waves. The ship was a state-of-the-art cargo ship with multiple water-tight compartments, an expert crew, and was considered unsinkable. It was lost with all the crew. The key evidence found was the starboard lifeboat which was recovered from the wreckage. The lifeboat hangs from forward and aft blocks 20 m above the waterline. The pins had bent back from forward to aft, indicating the lifeboat hanging below had been struck by a wave that had torn the lifeboat from the ship. To exert such force, the wave must have been considerably higher than 20m. At that time, the existence of rogue waves was

considered so statistically unlikely as to be near impossible. Consequently, the Maritime Court investigation concluded that an "unusual event" had led to the sinking of München[5].

Then freak waves were considered nearly mythical until one was measured at the new year's eve of 1995 at the Draupner platform in the North Sea off the coast of Norway (Haver, 2003). It may be seen that the significant wave heights were about 10 m (from crest to trough) when a wave some 25,6 m occurred (18,6 m over the mean water level). What is important of this record is that individual waves have been measured, while buoys used to monitor water waves are usually incapable of measuring individual waves since they only measure accelerations, with an accelerometer, which is a way of measuring the energy of the sea state.
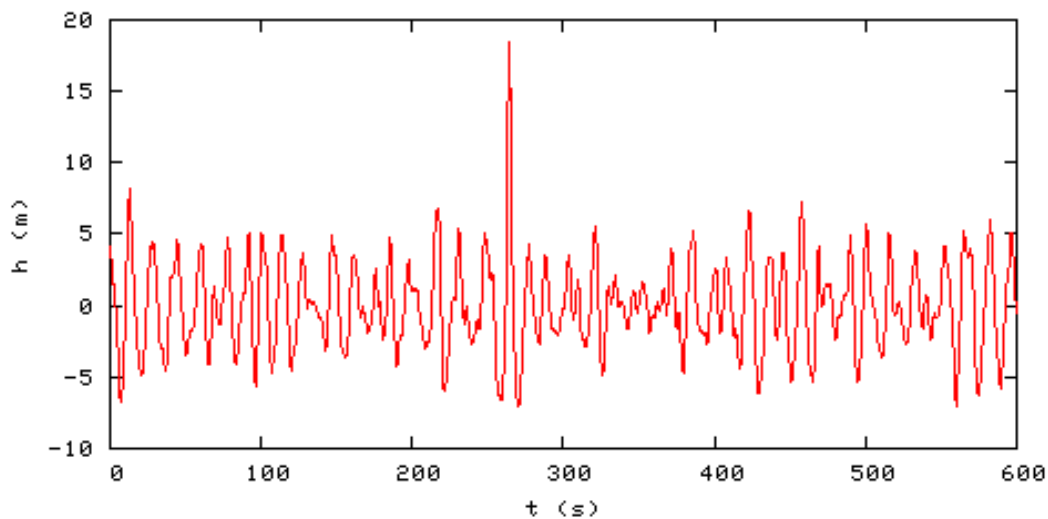


**Figure 20:** Record of the Draupner individual freak wave (from Haver, 2003)

The mechanism of freak waves is still being investigated, but it may be due to several causes, one of them the wave-current interaction, since a current opposing waves makes them higher.

### 4.1.3. Tsunamis

The last hazard for ships that does not appear much in literature due to the fact that if the damage is important it will be much greater at the coastal zone (that includes housing, cars, etc) than at the ships, that after all, are designed to keep afloat under unfavorable conditions.

Tsunamis occur only at certain areas of the world were the conditions are favorable. They are caused by earthquakes. It must be recalled that a tsunami wave is not caused by the vibration or the acceleration itself, but because of the sudden displacement of a "plaque" of sea bottom that causes a wave on the surface. Also, the vibration can trigger an underwater slide of material (with volumes of rubble much greater than that involved at the mountains and this displacement of material can also trigger a tsunami).

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[5]http://www.bbc.co.uk/science/horizon/2002/freakwave.shtml

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Tsunamis are not very well represented at films (where numerical effects and sometimes physical models are worked out for the show). Before the dramatic Boxer Day tsunami at the Indian Ocean in 2004 and the not less dramatic although with much less loss of lives tsunami of Japan 2011 it was not easy to watch footage of tsunamis (they are not really a very common natural hazard, fortunately) but now there is plenty of films to watch, mainly from the one at Japan. It may be seen that a tsunami is not a "*wall of water*" 10 m high destroying immediately everything it finds in its path but a very long wave that rushes in (with a high speed but not a crushing speed). In this way it is similar to a tide (this is the reason it is also called tidal wave), and its velocity can be easily calculated by a simple formula that is the shallow-water approximation for linear water waves. An original simple derivation is presented at Appendix 2.

$$v \approx \sqrt{gd} \qquad (4)$$

Where $g$ is the acceleration of gravity (9.81 m/s$^2$) and $d$ is the depth of the water at the considered point (in m). It is true that when a wave reaches land, it is a broken wave and its velocity is not so high because of the friction forces with the bottom, and also effects of wave- current interaction…However this formula I very exact when a tsunami moves through deep water and this is the reason that a tsunami shoals and increases its height to became destructive when it reaches the coast, The way a tsunami affects a coast is very determined by the geometry of the coast. The truth is that not everything is known about tsunamis, but in this text we will try to make an introduction.

What is important is that a tsunami where it is created has not a very important height, maybe it can only have height some 30 cm. But when they arrive to the coast, due to "shoaling" and the geometry of the coast, they may reach heights of tens of meters.

Tsunamis are an often underestimated hazard in the Mediterranean Sea and parts of Europe. Of historical and current (with regard to risk assumptions) importance are the 1755 Lisbon earthquake and tsunami (which was caused by the Azores–Gibraltar Transform Fault), the 1783 Calabrian earthquakes, each causing several ten thousand deaths and the 1908 Messina earthquake and tsunami. The tsunami claimed more than 123,000 lives in Sicily and Calabria and is among the most deadly natural disasters in modern Europe. The *Storegga Slide* in the Norwegian Sea and some examples of tsunamis affecting the British Isles refer to landslide and meteotsunamis predominantly and less to earthquake-induced waves.

It is not still well understood the formation and propagation of tsunamis and why very important earthquakes have not triggered tsunamis. The important factor about tsunamis is that they displace very important volumes of water. Tsunamis are waves that have periods of some 10-20 minutes. The period is the wavelength divided by the speed, and as we will see next, the speed or velocity of a tsunami is very easily calculated. The tsunamis are formed by a "train of waves", a few number of waves, some 5 to 10. The first wave to arrive may be a crest or a trough. If it is a trough it will be observed at a particular coast as the water retiring, depending on the geometry of the beach. The people that are at the beach may be curious and thus walk towards the sea to watch the seabed, and when the crest of the waves comes they will not be quick enough to retire, as they would have if they had retreated to higher zones when they saw and heard the sea retiring. A tsunami wave is usually not broken (it is not a "wall of water") except at some exceptional cases. The victims are caused by the rapid-moving water and all the debris floating around, since the water can hit buildings, causing them to collapse. Some people survive tsunamis, either by staying afloat swimming with nerve or getting hold of some floating object.

According to the shallow-water approximation, as we have mentioned, the speed of a wave in shallow-water, a consideration when the depth of the water is less than one-twentieth of the wavelength, is (see, e.g., Dean and Dalrymple, 1991). :

$$v = \sqrt{gd} \tag{5}$$

Where *g* is the acceleration of gravity and *h* is the depth of the water. In this case the wave travels at the same speed as the energy, so the "train of waves" maintains its profile as it travels. At Appendix 2 I present an original derivation of these formulae. Concretely, I derive the wave equation for long water waves.

Then the speed of the wave in deep, oceanic-waters, of an approximate depth of 4000 m (assuming g≈10 m/s$^2$) is then some 200 m/s (this is some 720 km/h). It is a very high speed but usually enough to give an alert to the coast with an hour in advance at least (so the coastal zones may be evacuated). The wavelength assuming a period of 10 minutes, some 600 s is then 120.000 m, say some 120 km. Thus, we may see that the shallow-water approximation is correct since the depth if the ocean is not deeper than 12 km.

However this situation changes as the waves approach shallower waters. At a depth of 10 m we find that the velocity, *c,* of the wave is some 10 m/s, a speed that very few people can attain. The energy, as we have commented, is proportional to the square of the height of the wave, so the flux of energy at a given point is proportional to:

$$E_f \sim c H^2 \tag{6}$$

It may be shown did since the energy is not easily dissipated, but only transported, assuming a tsunami wave approaching perpendicularly a straight coast we have that:

$$E_{f_1} = E_{f_2} \tag{6}$$

So operating we may find an estimation of the height of a wave at a given point is proportional to (making the assumption of wave perpendicular to the coast):

$$\frac{H_1}{H_2} = \sqrt[4]{\frac{d_2}{d_1}} \tag{7}$$

So if a tsunami at a depth of $d_2$=4000 m had a height of $H_2$=0.3 m, at a depth of $d_1$=5 m it will have a height $H_1$=1.6 m, which does not seem very impressive but we must consider that there are other factors when we consider the problem in two dimensions. The water entering a bay may accumulate at the end (particularly if it is a wedge-shaped bay). Also, refraction of the waves at the bottom may focus the waves to some point, such as an optical lens. So a tsunami also interacts with the coast and it is not easy to make accurate estimations of a tsunami at a given point. Once a tsunami advances into land no theory of water waves is valid.

The point is that normally it will not be possible to evacuate ships inland except at some very punctual cases. Instead, it may seem a good recommendation to head for the sea, to navigate greater depths where, as it is demonstrated, the height of the tsunami is very low. In fact, the word tsunami means in Japanese "harbor waves" since when the Japanese fishermen set for the sea they did not notice anything but when they returned to their harbor they found it devastated if this extraordinary event had

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taken place. Japan has the longest list of tsunamis but the most tragic one was that of the Indian Ocean in 2004, killing about 230,000 persons[6].

The tsunami of Japan 2011 has left us with millions of striking images, since it took place at a very developed economy. In fact, one of the worst effects was that that the barrier against tsunamis of the nuclear plant at Fukushima was overtopped and the diesel generator that would aid the cooling down of the nuclear reactor was destroyed by the overtopping water. The fail of a nuclear plant is always a "black swan", something unexpected that breaks all the assumptions, and so was this case, which has been fully studied so it will never repeat. In fact this was the only nuclear reactor that failed since 11 were automatically shut down after the earthquake.

So the main problems did not come from the harbors, much of which reopened short after the disaster, but from the cities. Harbors provide a barrier that halts the waters, although sometimes for a short time.



**Figure 21:** Photo of the 330-tonne Kyotokumaru, a fishing boat 60 m long that was swept 750 m inland when the tsunami reached the shoreline in Kesennuma (Japan, 2011). It may be observed that the structure of the ship has not suffered major damage (photo www.telegraph.co.uk). However, it was scraped.

Effectively, the recommendation of "*The Mariner's Handbook*", from the Admiralty (2004), is that "*a ship in harbour, either becoming aware of a large earthquake in the vicinity, or observing sudden marked variations in sea level, or receiving warning of an approaching tsunami, should seek safety at sea in deep water, and set watch on the local port radio frequency. After tsunamis, abnormal ground swells and currents may be experienced for several days*".

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[6]See, e.g. Parker, Bruce (2012). The Power of the Sea.

Almost all the countries in the Pacific Ocean participate in the International Pacific Tsunami Warning System and their seismic and tidal stations for a network covering that ocean.

### 4.1.4. Visibility

Accident statistics have revealed that a relatively large proportion of impact accidents, and especially collisions, occur in poor visibility. This is surprising, considering that navigation is dependent on radar and other electronic aids (so direct visual observation of fairway and traffic is not necessary). At modern simulators officers may also practice steering with poor visibility.

As a part of the traffic studies in the Dover Strait, the effect of visibility was also studied. It was concluded that the visibility factor was quite large and even greater than the effect of the particular encounter situation itself. A traffic separation scheme (TSS) was implemented in Dover Strait in 1977. Visibility may be defined in various ways, but in that investigation three cases were applied: clear, mist/fog and thick/dense (Kristiansen, 2005)[7]. Since the three cases are exclusive and they cover all the situations, a probability formula may be derived, that in this case studied is called Fog Collision Risk Index (*FCRI*):

$$FCRI= (P_1 VI_1 + P_2 VI_2 + P_3 VI_3)$$

$P_k$= Probability of collision per million encounters

$VI_k$ = Fraction of time that the visibility is in the range *k (k=1 clear; 2 fog; 3 dense)*

*k* = Visibility range

The estimated parameters of the model are shown in the following table:

| Visibility (*k*) | Clear | Mist/fog | Thick/dense |
|---|---|---|---|
| Relative visibility incidence ($VI_k$) | 0.9457 | 0.0446 | 0.0097 |
| Collision probability ($P_k$) | $6 \cdot 10^{-6}$ | $60 \cdot 10^{-6}$ | $1800 \cdot 10^{-6}$ |

**Table 1**: FCRI for the Dover Strait (Kristiansen, 2005).

The data show the dramatic effect of reduced visibility in collision risk. Although the frequency of thick/dense is less than 1%, the probability increases by a factor of 300. The resulting value for Dover Strait is then:

$$FCRI= (P_1 VI_1 + P_2 VI_2 + P_3 VI_3) = 25.8 \cdot 10^{-6} \text{ (collisions/encounter within 0,5 nm)}$$

The contribution of "thick/dense" on this figure is 68% (0.0097·1800=17.5), *e.g*, without the presence of this visibility condition the probability would have been 8. Of course, with modern radars, a human error

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[7]Kristiansen, I (2005): "Maritime Transportation. Safety Management and Risk Analysis. Elsevier. 508 pp.
This book is, from the ones consulted, the one that offers a most complete insight and application of probabilistic theory in navigation, offering a wide spectrum of examples. It also gives a deep insight in all the accident theories, except the Bowtie Model (but it explains Tree Analysis). It is thus a highly recommendable book, although the examples, of course, are constrained to particular situations of space and time.

must also take place for an accident to occur. But, as usual, in optimal conditions (good visibility, unstressed crew, etc…) accidents are less prone to occur. In this example, it is quantified that the probability of having an accident conditioned to mist/fog and thick/dense increases 10 and 300 times, respectively.

In this case we see that the probability of accidents in certain conditions may be estimated from simple observation and counting, but we must control that all the factors remain constant with time.

## 4.2. The human factor

According to 30% of the accidents are caused directly by human error and 80% indirectly (according to Rodrigo de Larrucea, 2015, that references official reports of maritime accidents). The direct accidents include the indirect accidents, so we must ask ourselves what does this difference of 50% mean (half of all the accidents). I assume that it means that these accidents could have been avoided by a proficient seamanship of the crew, specifically of the captain.

The human factor is at the center of most of the accidents. It is true that if everybody acted in the best way possible, which is the aim of the formation as seamen, most accidents would have been spared. But perfection is difficult to attain…excellence is then the aim.

Others cannot be attributed to human errors, for example the grounding of the tanker Urquiola at a Corunya (Spain) on 1976 was at a shoal that was not represented at the nautical charts of its time (see the very recommendable article of Jar, 2005). In the aftermath of the grounding, that at first was a simple leaking of oil, bad decisions taken by the port Authorities, that at that time were military, caused the leaking to increase and finally the boat catching fire when it was almost evacuated, since the captain of the ship, Francisco Castelo, 41, chose to stay on it (in that time an abandoned ship could be claimed by anybody), with a pilot of the port of a Corunya. Finally there began some explosions and the two men jumped to the water, but only the pilot survived. The efforts to put the situation under control were to praise, in a Spain that was in a rapid change from a Dictatorship to a democracy, but not the legal actions taken by the Marine Administration that applied an Spanish saying: "*echar la culpa al muerto*", this is, "blame the dead" (it was also a way to avoid paying reparation costs for the government). It was not only until 1983, thanks to the fight of his widow, that the honor of captain Castelo was restored, and his heroism recognized. It was a time in Spain when merchant shipping depended on the military. The case is well documented with photos, nautical charts, in the referenced emotive article written (in Spanish) by Luis Jar Torre (2005).

I think the explanation of this case is illustrative, without going into de details, since if somebody was making statistics of accidents in 1980, this case would have appeared as a human error. Fortunately many things have changed in these last more than 30 years (in Spain).

Also, the watchmen of the Titanic in 1912 saw the fatal iceberg in the moment they saw it (even there was good visibility and full moon) because the waves were so small that they did not cause foam at the base of the iceberg and made no sound. The maneuver made by the Titanic could have been better maybe, but the Officer-On-Duty was not trained to carry it.

Other accidents, however, may be directly attributable to a human error. It is true that there can be several causes, and in the aftermath many different topics will be discussed, but with a perfect behavior from the human, the accident would not have taken place.

The research shows that mistakes are usually made not because of deficient or inadequate regulations, but because the regulations and standards, that do exist, are often ignored. The IMO MSC (Ziarati, 2006) clearly indicates the causes of many of the accidents at sea are due to deficiencies in maritime education and training (MET) of seafarers or disregard for current standards and regulations. Ziarati also reports (2007) that majority of accidents and incidents are related to collisions or groundings.

Probably most of these collisions and groundings take place not at open water, where it is easier to maneuver, but at restricted areas, ports and waterways, where there are also some hydrodynamic effects that are maybe more complicate to master (under-keel clearance, squat effects and interaction between hulls). Fortunately, the speed of navigation at ports and waterways is normally limited, at ports there is also the pilot and the tugs that are real experts at navigating at their place.

One topic that can be found in some literature is that ancient seafarers were better in some aspects than modern. It is true that ancient seafarers at the past were at the "crest of the wave", in the sense that navigation was a complicate technology and career and thus only the most capable were able to dedicate to it. It is true that in those times (before the industrial revolution, we think), there were not many things to do at land. Thus, ancient seafarers could be compared to present-day astronauts, expanding the knowledge of our world riding state-of-art machines and bringing news about foreign places. With the industrial revolution come new technologies at land that were also applied at the sea, like the vapor machine. To master navigation by sail was still important but no longer totally necessary. There were new jobs aboard such as the chief-engineer and firemen. After came radio-communications, with new jobs such as the radio-officer. Even though the captain was still the main responsible for the ship, he began to have powers under him that he did not fully understand (to understand how the wind blowing moves a ship is not simple but must be understood, however, how a radio works may not be understood, simply). It is maybe at this moment that the roles at the ship cease to be as military as before (with the captain on top), and they become more industrial, with the captain always responsible for the whole but with some tasks that are out of his control (keeping the motors running which is the task of the chief engineer, or the radio working). The crews get reduced when the engines become of gas-oil, and also as the radios become simpler, radio-officers disappear.

Nowadays also seafarers have lost their ancient glamour. Maybe some of it has passed to airline pilots that carry the lives of several hundred people through the air in machines that maybe aren't so much different in technological sophistication than a modern ship but it seems so, since it flies while a ship progresses over the sea surface at a speed usually not greater than that of a small motorcycle. Also, two pilots drive it safely, while at ships, only at the bridge, there is usually the captain and three officers. And it is true that nowadays at land there are many interesting professions.

### 4.2.1. Drugs and alcohol addiction

The limited crew size, isolated environment and concentrated workload are factors that support the truth that drug addiction and alcohol abuse have no place on a ship. They are a cause of several disasters, and evidently, we do not know the cases "near misses" since the addicts take special care to hide.

There are rules in places that specify alcohol content in blood, above which a person is not fit for watch keeping duties. Some limit it to 0.04%. Consuming alcohol during the previous four hours also leads to

the same disqualification. In, January 1, 2012, came into effect for the first time under STCW 2010, mandatory limits for alcohol consumption: a limit no greater than 0.05% blood alcohol level (BAC) or 0.25 mg/l alcohol in the breath[8].

Some companies now have put the limit on the 0% consumption. Normally those companies that have alternating crews have this 0% tolerance, since half the time the crew is at their home and there they can drink what they want.

In this section about alcohol and drug consumption, we are going to devote some space to maybe the most studied case of alcohol consumption in history, according to Luis Jar Torre, a case that in 1989 shocked specially the American public, without being one of the major oil spills in history (some 37,000 tons at the pristine waters of Alaska) and with the luck that the ship did not break nor explode, it was repaired and continued to navigate under a different name (in fact, it has had at least four different names, without Exxon in it). The name of the ship is thus Exxon Valdez, and the name of the captain Joe Hazelwood. Many years have passed but he will be always regarded (as he himself recognizes) as the drunken villain of the US merchant fleet. It did not help, that, at the moment he had the accident, the captain had his driving license retired for driving drunk, and that in the past five years, he had suffered other 2 arrests for this cause. The night of the accident he had abandoned the bridge to his third officer, so he would carry the maneuver to reach open waters. In 1989 Hazelwood was 42 years old and many considered him the best captain of the company. He had a very good "curriculum", had studied at the prestigious Maritime College of the University of New York, had been sailing from his 22 years and commanding ships at Exxon from his 32. When half the country claimed for his head, those who had known him aboard, without exculpating his errors, praised him: "*highly skilled, highly qualified*", declared pilot after pilot to the Coast Guard…"No one had anything negative to say about Hazelwood's seamanship", added the investigator of the NTSB. An intelligent guy, but there are reasons to think that he was also introverted, and he had also problems at home (he was married, one daughter): a bad combination to take into a tanker. In 1984 half the fleet knew "the old man" had problems, even though the "dry law" at Exxon's ships, the captain drank, invited his subordinates and was object of jokes ("*It's Captain Hazelwood and his Chief Mate, Jack Daniels, that runs the ship*"). In words of one of his mates, it was as if he was trying to get caught. The problem became so obvious that his supervisor (and friend) convinced him to go to rehab in April, 1985. A doctor found him "depressed and demoralized" but Exxon gave him a route near his home in New York. According to the Coast Guard, he would have lost his license as a Captain when he renovated it in 1986 if he had told his problems with Traffic ("If they lie on the application, that becomes a fraudulent application and it voids the license …/… Drunken driving convictions are not minor traffic violations"). However, in 1987 they gave him the commandment of the flamboyant "Exxon Valdez" and that year and the next the ship won the price of the Company to safety.

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[8]http://www.professionalmariner.com/December-January-2011/New-STCW-crew-rest-hour-alcohol-rules-go-into-effect-Jan-1/
"Each Administration shall establish, for the purpose of preventing alcohol abuse, a limit of no greater than 0.05% blood alcohol level (BAC) or 0.25 mg/l alcohol in the breath or a quantity of alcohol leading to such alcohol concentration for masters, officers and other seafarers while performing designated safety, security and marine environmental duties". Convention Ref: STCW Section A-VIII/1 Article 10

Lamentably, in September 1988, after 19 years of marriage, he was again on the brink of divorce and had another time his driving license retired for drunk driving. If he drank aboard, it did not seem to affect his skills, for which he was well-paid (some 100.000$ of the time yearly, and since there were alternating captains, with the possibility to be at home plenty of time).

There were three officers or mates at the ship that after all were the ones that had to take care of all the guards while the tanker was charging all the oil. It is true that in many enterprises or companies, in typical situations, the middle-classed have more working hours and stress than the ones that "have made the top". The captain bears the responsibility of its three (or sometimes four officers) but if they work well, then he can relax more than his subalterns. This is what happened that 23th March, 1989, Easter. Joseph Hazelwood went to land with the Chief Engineer and the Radio Officer. After some paperwork, the trio met at the "Pipeline club" at the afternoon:  the drinks at the "Pipeline" are thus, perhaps the most investigated in history. Hazelwood came at 16:30 and he drank 3 vodkas. Then he took another drink at "Club Valdez". So he calculated "*at least three drinks*" and the Coast Guard recalculated "*may have had four*". Well, resuming, the Captain appeared at the bridge at 20:30, at 20:40 he had a reunion with the Pilot and the Consignee. None of them noticed if he was drunk but the Pilot would declare later that his breath smelled of alcohol.

So besides three fatigued mates and a "*loaded*" Captain, the Exxon Valdez carried some 181.000 tons of crude oil through a difficult route, with ice and reefs, in a natural park at night. The Pilot called for the Captain at 23:05, near the limit of the zone of Obligate Piloting, and he appeared at 23:10 at the bridge. The presence of the Captain was obligatory since only he at the ship had the special license to navigate North of Bligh Reef, where they finally grounded. The Pilot left, and Hazelwood informed "Traffic Valdez" that he accelerated to cruise speed. The third mate, 22 years old, so without much experience, should have ended his watch at 24:00 but he stayed there since it was the key maneuver to get into route. The "Old Man" explained to the young the maneuver, asked if he was "*comfortable with the procedure*" and if so, he would go to his cabin to finish some paperwork. The novice said so (what if he said no?), so at 23:53, in his most unfortunate act in 20 years of sailing, he disappeared from the bridge. The exact hour of grounding is approximately 00:07 and the third mate had phoned the Captain a minute earlier "*I think we are in serious trouble*". In the aftermath of the grounding the Captain could do nothing, fortunately, since any movement would have worsened the situation. The Coast Guard officers that came aboard the ship at 3:30 declared that the Captain acted normally although his scent was of alcohol (maybe some minted chewing-gum would have been an aid). At 10:20 in the morning a specialist took the blood and urine samples. The story about these samples continues and is found at the reference (Jar,). Finally, 23 March of 1990 a jury absolved Hazelwood of "*driving a watercraft while intoxicated*", being finally condemned to 1000 hours of community services. The Coast Guard also sanctioned him with 9 months of his Captain License retired for "*violating Coast Guard policy on drinking liquor prior to taking command of a vessel, and of improperly leaving the vessel's bridge*", and was fired from Exxon. It is true that the general impression of this accident is that in the trouble, the man who had the better formation, the best chance of not being fatigued, was not at his place, with or without the help of alcohol.

**Figure 22:** Photo from 26th March 1989: "Exxon Valdez" is stranded and surrounded with skimmers (antipollution barriers) while the "Exxon Baton Rouge", smaller at its port side, is loading oil. It may be observed the goodweather and the occasional presence of ice from Columbia Bay (Photo Erik Hill - Anchorage Daily News).

In the aftermath of the Exxon Valdez, all the navigation protocols were strengthened in Prince Sound, Alaska, and to this day no other disaster has occurred. I do not want to draw any conclusion on the life of the Captain, or the role of the Company. Exxon is a very important company but generally keeps a low profile. These companies may run their own ships (which is safer in theory, but not in this case), or they may charter ships. As usual, the lesson has to be learned through experience.

Also, I would also like to point out the figure of another Captain whose use of alcohol does not seem to affect his seamanship, and serves as a caricature of seamen at a time where drinking aboard was considered an admissible vice, in order to stand the hardness of the work when the ships were not so modern. I refer to Captain Haddock, from *Tintin* comics by Hergé, who gives the replica to this young reporter who never publishes. It is true that for my generation that grew without internet, the most popular international comic was that of *Tintin* (although not the only one, evidently), and in some of his albums navigation has a major role and the sympathetic figure of this captain, stubborn and simply drawn, sometimes cursing has a characteristic that maybe would not make him suitable for our society that is much more sensible to education than that of the sixties (also, this is a very competitive society): he was an alcoholic.

For the generation of European baby-boomers, born in the sixties and seventies, Tintin's comics were the first introduction to a world where the model of the merchant marine captain was Haddock. Curiously, there have been even books edited about his navigations, but at almost all his ships he was the only seaman aboard (a kid does not notice this incongruence). It is true that new generations they

have better or at least more varied models to look at (as a fact, youngsters today do not read Tintin). The first appearance of Haddock dates back to 1941 ("*The Crab With the Golden Claws*") and maybe this first album offers the most complex, critical and introspective view of the Merchant Marine (later on, Haddock becomes a rich "socialite", having nothing to do with navigation).



**Figure 23:** Captain Haddock, in images that nowadays would not be considered suitable for children, maybe. It may be observed that the three golden lines at the Captain's uniform indicate First Officer, not Master, but well, it is only a comic (from *Red Rachman's Treasure*, 1943, and *the Shooting Star*, 1942, by Hergé).

### 4.2.2. Fatigue

A lot has been written about fatigue and burn-out syndrome at jobs. Fatigue may be considered punctual while burn-out syndrome has the connotation of an unsatisfactory situation continuing after longtime. Both can be avoided principally by resting enough hours having good sleep (sleeping is very important for health: some people may need more sleep and others less but the consequences of bad or not enough sleeping are well known and we will not insist In this work.

Nowadays, most employers have understood that it is on behalf of the economy to leave enough resting hours to the crew. The human is the most fragile piece of a ship and if it fails everything can collapse.

The International Chamber of Shipping is reminding shipowners that the new STCW 2010 minimum rest hour requirements are likely to be vigorously enforced by Port State Control Officers which demonstrate they have been provided with the required minimum rest. For example, seafarers must now always have at least 10 hours of rest in any 24 hour period, except during an emergency[9]. According to the Paris MoU, the greatest number of deficiencies in 2014 was in the documentation: "*Records of seafarers' daily hours of work or rest*", with 11.38% of the deficiencies[10].

Concretely, in Section A-VIII/1 of STCW 2010 there are the following Articles (amongst others):

"*1. Administrations shall take account of the danger posed by fatigue of seafarers, especially those whose duties involve the safe and secure operation of a ship.*

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[9]http://www.nee.gr/downloads/111Guide%20for%20Seafarers.pdf
[10]https://www.parismou.org/sites/default/files/Addendum%20detailed%20MLC%20figures%202014.pdf

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2. *All persons who are assigned duty as officer in charge of a watch or as a rating forming part of a watch and whose duties involve designated safety, prevention of pollution and security duties shall be provided with a rest period of not less than:*

*.1) a minimum of 10 hours of rest in any 24-hour period; and*

*.2) 77 hours in any 7-day period.*"

As in the previous text about alcoholism, where the most known case was presented even though it was very old (from 1989), here I will present an even older and also very studied case, since it was the first important oil spill in history and it affected many people. In the case of an oil spill, the public opinion was informed during months about its evolution, and the first case was *Torrey Canyon*, 1967.

In its time it was one of the greatest ships of the world, with length 297 m and 117.000 tons deadweight, a pride of ship manned by a first-class crew. However, studying the case, some curiosities appear: it was owned by a North American company established at Bermudas Is., Insured at London, flag from Liberia, manned by Italians, chartered for a trip by the company British Petroleum. A morning of March a long trip from Kuwait, via South Africa, was going to end at Milford Haven, but the ship grounded on Seven Stones reef between the Cornish mainland and the Scilly Is.

In the aftermath search for the responsible, the Committee concluded that *"…the Master alone is responsible for this casualty*"[11]. Five years later, after an exhaustive study, the conclusion of Commander Oudet, of the Royal Institute of Navigation, was that since there was not a rational explanation for his behavior, the explanation must be thus "*irrational*"[12].

The details of the case may be found again in a long article, in Spanish, by Luis Jar Torre (1999). Resuming, there was a bad relation between the First Officer and the Captain, Rugiati, 57 years old, with more than 20 years commanding tankers. However, he had been on board exactly twelve months and a day, he suffered insomnia, nervous tics and also tuberculosis, which was immediately apparent after the accident (he was hiding it). The First Officer had been on board a similar period.

What happened has been object of many commentaries, some may vary a little, stressing more importance at some factors (whether the Captain was in a hurry, the automatic pilot) than others. This is not important for our point. An accident usually has many causes, and here we are going to stress the importance on the first link of the chain, when things began to diverge from the straight course. When the First Officer that was on watch found the Scilly Islands on the radar he corrected the course so they appeared straight ahead and he called the Captain (that had left written to be awaken when they appeared), so that he would decide to leave them port or starboard. The Captain asked him if with the initial course they left the islands at board and the Officer told him so, although they were still too far to calculate exactly. Then the Captain asked him, not friendly, who had given him the order to change course. So they left the initial course that at that moment did not clear exactly the islands, but the Captain did not want to correct "his" course again until the First Officer had cleared from the bridge,

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[11] "Report of Liberian Board of Investigation", 1967
[12] Oudet, L.: "In the Wake of the Torrey Canyon", 1972

which would happen in half an hour, at 8 O'clock when a young and thus less experienced third officer entered the watch. During this time, the Captain and the First Officer did not share a word. Finally, it was too late, the Captain took a bad decision to pass between the Islands, he also got confused with the automatic pilot and the result is known.

This accident began to change the navigational policies of the companies, giving more vacations. In Spain at that time the merchant officers envied de Navy since the military could be sent to a long and far mission, true, but after that they could choose another destiny at land or near home. There is a term in English to describe a particular mental disorder of a seafarer (maybe it is not so used nowadays, thanks to the better conditions): tankeritis. In Spanish it is called "*mamparitis*" (it would be translated exactly as bulkheaditis) and Luis Jar was surprised after many years of sailing and at ports (without arriving himself to be Captain) to see how many Captains were affected by it (he comments this at his article about the Torrey Canyon, Jar 1999). He comments that the Captain is maybe the loneliest person at the ship, since other Officers can count on each other. He does not comment much on the chief engineer who traditionally worked without really between bulkheads, without the sight of the sea. Today a simple search of "*mamparitis*" on the web only brings some anecdote and references to books of maritime sociology that very probably have become outdated, since the world has changed a lot.
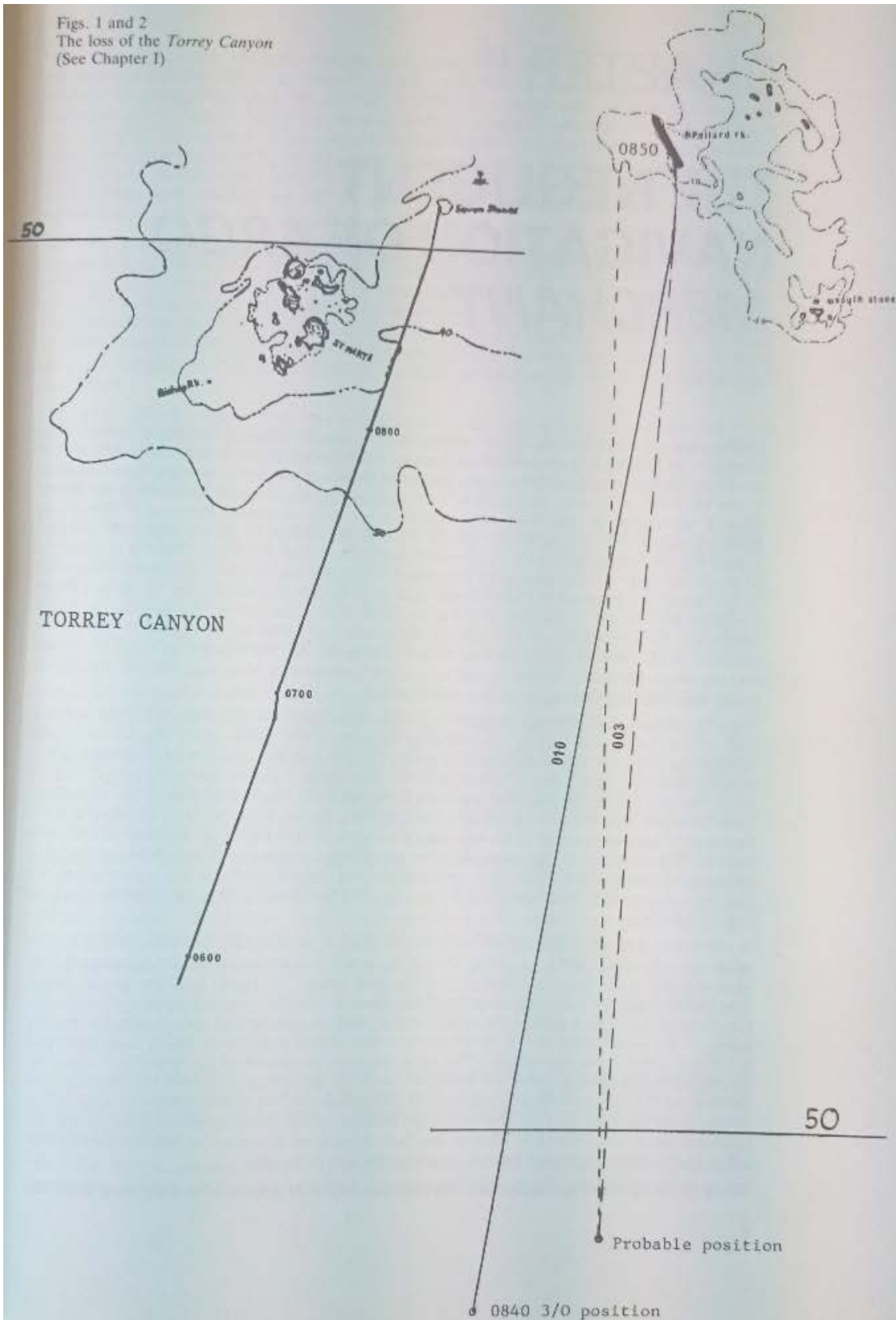
**Figure 24**: Probable course of the Torrey Canyon before grounding at the Scilly Islands. The zoom is at the right but at the left we may observe the minimum change of course set by the First Officer and that was quickly corrected by the Captain. This meant the beginning of the situation escaping from the Master's hands and finally causing the stranding (from Cahill, 1985, p.7).

**4.2.3.Workaholics**

Since in Spain there is a saying that goes "there is not 2 without 3" (and there have been three major oil spill accidents affecting its coast: Urquiola, Aegean Sea and Prestige). I would also like to present a third case of a major oil spill. Very well-known, also, although not as much as others since the year when it took place, 1992, Spain was developing very quickly, with the Olympic Games, the Expo of Seville, the 500-Anniversary of the American discovery. Thus, they preferred to leave the problems behind, not like with the case of the Prestige(2002) that was heavily publicized. In this case the Captain is not a drunkard, nor is he depressed. This Captain would be in theory the dream of any maritime employer: someone who loves the sea, his ship, does not want to take vacations, etc... This is perfectly possible, there are people that love their work, and thanks to the work of many workaholics we have better computers, etc...

This could have been the case (although now it is also difficult to contrast, after so many years, but what is important is the possibility, the feasibility) of Captain Constantine Stavridis, a pretty young captain, some 40 years, that commanded the Aegean Sea, an OBO (a tanker that can also carry bulk, usually more maneuverable than a classical tanker). He was always impeccable; he had the confidence of his employers: according to an internal report of the Spanish Authorities, during the more than 6 years that he commanded the Aegean Sea, he had only four months off vacations, and when he had the accident, he had been 30 days aboard. His career, however, ended quickly a bad night of 1992.

It was the first time he entered the Corunya Port in Galicia, Spain, December the 3rd, 1992, and at night and with bad weather he tried a difficult and daring maneuver to meet the pilot at a sheltered zone. According to the evolution curves of his ship, it was perfectly possible, but with wind, waves and bad weather, the papers became "wet papers"; she could not complete the delicate turn and grounded on the rocks (the remains of the ship rested there some years until they were scraped; it became a touristic attraction since it was the seafront near the ancient lighthouse of Hercules, a popular promenade at this marine city).

In this case we cannot know the Captain's opinion since after paying the bail to get out of preventive prison, he fled and the judge never saw him again. Maybe he did not have much confidence in a legal system that had shut him immediately in prison after taking a shower at the hotel and now he is sailing around the world...

**4.2.4. The Human Factor in Accident Investigation**

We usually think of an accident as an unexpected event, certainly unintended and with distinctly unpleasant outcomes. A "true" accident is, almost by definition, neither controllable nor predictable. By way of illustrating this point, we would not normally consider the failure of a light-bulb to be an accident.

The same thing cannot be said for the behavior of human beings. It is because the nature of the human element cannot always be known in advance with absolute certainty, and more difficult to manage or contain in consequence.

The investigator must keep firmly in his mind that all information available to him is permeated by the human factors, including his own, involved in the very process of data collection itself.

In developing a list of questions we may find it helpful to consider a number of alternative viewpoints about what constitutes an accident. Thus:

1) The accident may be a pure chance event
2) The accident may be due to some characteristic of the actors
3) The accident may be a result of a particular interaction between the actors and the situation they find themselves in
4) The accident may be caused by social or cultural factors

There exist personality stereotypes, too. For example, it is often maintained that there are certain types of people who are particularly prone to accidents. This commonsense notion is, however, not supported by psychological research. It may be more useful to the investigator to think more in terms of attitude of a particular actor towards his task, or safety in general. There are a whole range of motivational issues which might be considered. Attitude and values but also "risk perception" and "expectations".

The interaction between an actor and the situation he finds himself in is a particularly useful perspective. The concept here is comparable with a "disease model" in which some sort of "disease agent"

In a particular casualty we were to suspect that fatigue may have played some part in creating vulnerability to the "disease", we should then want to know the details of the watch system aboard ship, the hours worked in the preceding period and whether or not those involved had eaten and slept properly.

Other answerable questions arising from the interactive viewpoint relate to the exact timing of the accident.

In considering the human factor in accident investigation, the surveyor has to accept that all information available to him is permeated by the human factors, including his own, involved in the very process of data collection itself. For example, the investigator may find that he has to rely heavily on the reasons that one particular witness gives for his actions, but for these reasons to constitute a "valid" explanation some overlap will be required in the value systems of both the witness and the investigator.

It may be helpful for the investigator to approach the accident from a variety of different perspectives in order to gain as complete a picture as possible of what happened. Given that the information about any particular casualty can never be 100 per cent "total", the proposition is that we may gain deeper insight into an incident by "illuminating" it with questions from different perspectives.

**A "check-list" approach**

Depending on our particular education, background and set of individual prejudices, we would all no doubt formulate a different set of questions suitable for investigating the human factor in accidents. There is no substitute for the initiative and intuition of the individual surveyor, but some uniformity of approach, perhaps along the lines of a check list, may help the inferential process.

A check-list can spell these out in a systematic manner

Thus, the following accident "dimensions" may be listed:

- Geographical (e.g. position, area, distance from land)
- Weather, etc

- Time worked in the last week



Question 13 - Reasons for Manoeuvres Contrary to Colregs
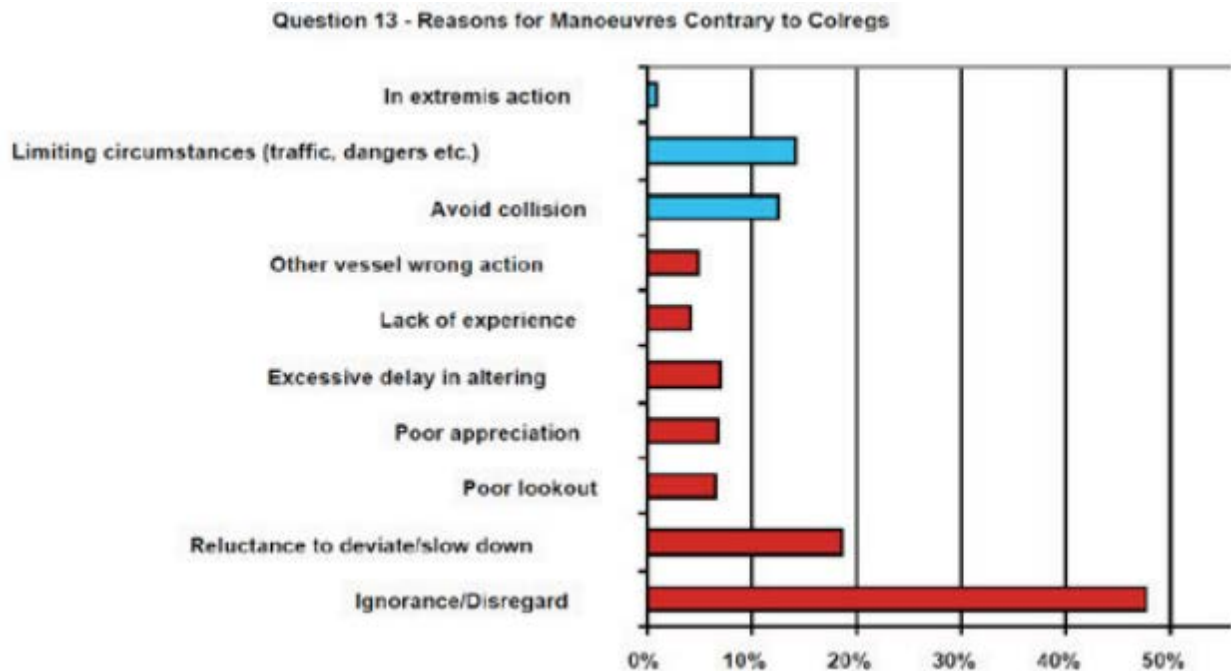
**Figure 25**: Reasons for maneuvers contrary to COLREG (from *Acar et al*, 2010). It may be seen that all probabilities add slightly over 100%, so in some cases, there may be two causes (e.g. lack of experience and another). The blue causes are justified, the others no and they must be considered flaws of the human factor.

Ziarati (2006), found that in some cases, maneuvers contrary to COLREG were due to the fact that the conning officer did not know sufficiently these regulations. In fact, this is a major cause,as may see in Figure 25 (Ignorance/Disregard at some 47% of the causes). Thus, if the human factor is the main cause of accidents, a simple way to cut down the accidents, according to Ziarati, would be to intensify the knowledge of COLREG amongst deck officers (with conferences, examples, etc…). The most important part is maybe Part A and Part B that consist of 19 Rules that are not so simple (since they regulate the relation between all types of ships in all conditions). Part C (lights and shapes) is also very important.

## 4.3. Mechanical failures

As we have seen, and also according to Capt. Cahill (1985) "human error accounts for the overwhelming part of strandings, but not a insignificant number of such casualties result from steering or machinery failure…Unfortunately, there is ordinarily little the Master can do to forestall mistakes in an area in which he usually lacks competence but also will not have direct access to the relevant information and facts. As far as the propulsion of his ship is concerned he is ordinarily little more than a passenger".

For a passage planning, one can consider a loss of steering, of propulsion, or both. In much such cases an eventuality will not expose the vessel to immediate hazard, since it is more probable that the vessel is at open sea and the machinery will be restored to operation in good time (or help received from

salvage ships). However, when the vessel is restricted in its ability to maneuver close to land, the failure to take this possibility into account may be the difference between a near miss and a stranding.

A pretty recent legal case where there has been a discussion whether the problem was the structural flaw of a floating object is the case of the rig "*Cendor MOPU*" (ex "*Odin Liberty*"), examined in an article by Templeman, M (2011)[13].  The oil rig was purchased by the assured (Syarikat) for conversion into a mobile offshore production unit for use in the Cendor Field, off the coast of East Malaysia. The insurance covered the loading, carriage and discharge of "*Cendor MOPU*" on the towed barge "Boabarge 8" from Galveston in Texas to Lumut in Malaysia.

"*Cendor MOPU*" was laden on the barge with her extendable legs in place above the jackhouse, rising some 300 feet into the air. Both assured and insurers understood that her legs were at risk of fatigue cracks during the voyage. The voyage commenced on 25 August 2005. On 10 October 2005, tug and tow arrived at Saldanha Bay, just north of Cape Town. On the evening of 4 November, the rig's starboard leg broke off at the thirty foot level and fell into the sea. The following evening two legs also broke. The assured claimed on the policy, on the basis that the proximate cause of the loss was the perils of the sea. Insurers rejected the claim, *inter alia*(among other things), on the basis that the loss was caused by inherent vice. They claimed that "*Cendor Mopu*" had an inherent vice that prevented it from carrying the trip as planned.

On the findings made by the first instance judge, the loss of the rig's legs resulted from metal fatigue, a progressive cracking mechanism initiated at the corners of the pinholes in her legs and caused by repeated or fluctuating stresses each (in itself) insufficient to cause a stress fracture. The stresses resulted from the action of the waves encountered by the barge on her pitching and rolling motion. The weather and sea conditions encountered on the voyage were not unforeseeable or abnormal, and the judge found that failure of the legs as the barge was towed around the Cape was very probable but not inevitable.

The court, however, concluded that the loss was caused by perils of the sea. Insurers appealed to the Supreme Court, who dismissed the appeal stating that "*The fact that weather and wave conditions encountered on a voyage may be foreseeable or reasonably expected does not (without more) preclude recovery for resulting loss as a loss caused by perils of the sea*"[14] (In the words  of Professor Howard Bennett, quoted by Lord Clarke). Preclude is to prevent from happening, make impossible. So these were good news for shipping companies and not so good for insurance companies.

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[13]Perils, Exclusions and Loss: Recent Marine Insurance Cases(http://www.lawgazette.com.sg/2011-04/75.htm)
[14]*Global Process Systems v Syarikat Takaful Malaysia* **("Cendor MOPU").**Lord Saville, paragraphs 31, 36; Lord Mance, paras 78, 80; Lord Clarke, paras 104, 128, 138.*
**(**https://www.supremecourt.uk/decided-cases/docs/UKSC_2010_0006_Judgment.pdf)

**Figure 26**: Oil Platform CENDOR MOPU being towed this time successfully in 2014 from Malaysia to Batam, Indonesia (photograph from http://www.marinelink.com/news/successful-completion381631.aspx). The legs standing some 90 m over the water may be observed. It seems that the stability of the legs could have been enhanced by staying diagonal cables between them (making the system more rigid, which do not seem to exist in the photo).



**Figure 27**: Platform CENDOR MOPU in place (from http://www.sediabena.com/oil-gas.html). 40 men live there.

Another case that we are going to study in detail due to its importance is that of the ferry Estonia. In this case, the cause of the foundering was a mechanical failure but bad weather and a not optimal human

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Facultat de Nàutica de Barcelona

management of the resources played also a significant role on the tragedy. Most of the information is from the excellent article from Jar Torre (2008), in Spanish.

On 28th, September, 1994, MV Estonia, an impressing ferry that linked Tallinn with Stockholm, lost its prow facing a "normal" gale and 852 people lost their life. There was such a commotion that the next day the ministers of Estonia, Sweden and Finland had reached a deal and created a commission: the "Joint Accident Investigation Commission" (JAIC). The presence of Swedes and Finns in this commission (presided by Estonia) could be explained because the first had the majority of the victims and the seconds coordinated the rescue. So, even though the ferry was crewed and flagged in Estonia, 50% of the property of the ferry was Swedish, and Swedishwere the nine "consultants" that sailed aboard.

Sweden and Finland brought into the JAIC a respectable panel of experts, and its encyclopedic final report, in 1997, reflected, *"the vessel was seaworthy and properly manned"*, pointing as a fundamental cause of the accident that the design of the prow was manifestly improvable. The prestigious German shipyard "responsible" of the prow considered that what could be improved was the report, so it financed a "German Group of Experts" (GGOE), supposed independent, whose "counter-report" (thousands of pages long) saw the light in 2000; synthesizing, the GGOE went to say that the ferry lost the prow because it was bad maintained and not well manned. Two reports that are the fruit of an impressive investigation, each one matching finally its conditionings. There were also "conspiracy theories" that include secret cargos, spies, mafias, bombs, submarines, etc...

The easiest way to go from Helsinki to Stockholm is to take a ferry, so from 1960 and in some 15 years the number of particular cars transported by sea between Finland and Sweden was multiplied by ten, and that of trucks for more than a hundred. The two main companies that served this line were the Silja Line and the Viking Line, both with Swedish-Finn capital and similar problems to cover a demand that forced to reinvent the float continually. With only seven years the ships were obsolete and in the first nineties some units of some 60.000 GT were in service; so, when JAIC stated that the traffic *"... probably progressed faster than international regulations and the classification societies could accommodate"*. These ferries seem to be great moles with hugebuoyancy and stability reserves, but to practical effect, its bulkheads end at the ro-ro garage, a gigantic "garage" that runs from stem to stern and from board to starboard some two meters above the Plimsoll line. At the first ferries the access to this deck was a door-ramp at the poop, but son it was seen that, opening another one at the prow and alternating the mooring at each port, the discharge of vehicles was quicker. Obviously, a very big door without any compartmentalization facing the waves seems at least dangerous.In 1990 captain and writer Richard Cahill described the ro-ro ferry as *"Inherently Unseaworthy"*.

The Baltic ferry soon evolved towards a"subspecies" of high occupation and low tariffs, compensated by the money that the tourists spent aboard. Draught-Restricted, the ships grew in height and beam, and they became more potent and maneuverable (to overcome winds, ice). Unfortunately, the fact of sailing at a closed sea also caused excesses of confidence. The construction time of the "Estonia" was of only eight months and eleven days. The keel was fitted the 18th October 1979 at the Meyer Werft shipyard (Papenburg-RFA), a really modern shipyard by the time, and it was delivered to its ship-owners just in time for the high season... but without a part of the cabins for passengers finished; its name then was "Viking Sally". When it entered in service in 1980, the 15,598 GT of the "Viking Sally" made her the second biggest ferry in the Baltic: it had a length of 155.40 m, beam 24.20 m, 7.65 of draught to the "ro-ro" deck and 5.60 m of maximum draught; four diesel motors of 4,400 kW connected by pairs to two

variable pitch propellers that gave a service speed of 21 knots (90% of the power), and two lateral propellers at the prow.
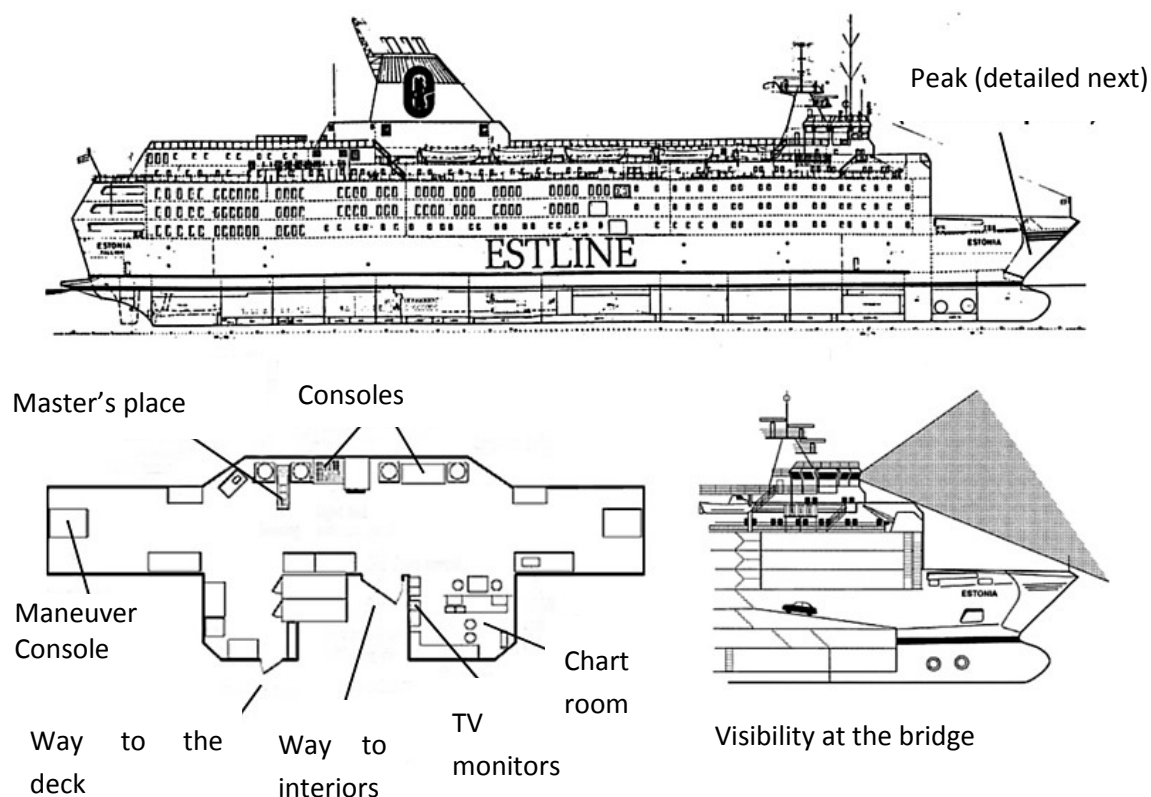


**Figure 28**: Profile of MV Estonia, disposition of the interior of the bridge and sector of visibility towardsthe prow from the bridge (from Jar Torre, 2008).

Under the garage of "Viking Sally", apart from the engine room, and the double bottom there were two public decks: 0 (saunas and pool) and 1 (economic cabins for 358 passengers. There were also 15 water-tight transversal bulkheads.... "*equipped with watertight doors as required*". Over this potential"Swiss cheese" there was 150 m of garage (Deck-2), accessible by foot from 11 sliding doors. As was usual before 1985, the prow of "Viking Sally" was "peak type" (see image), made of a ramp of 12 tons and a "lifting peak" of other 56 that, powered by two hydraulic jacks, rotated 90º in vertical over two hinges in the deck of the castle. To set out for the sea, first the ramp was lifted, and was pushed against its frame by two big hooks and immobilized by four hydraulic bolts; then the prow was lowered until it rested in position, being lashed by other three hydraulic bolts that passed to the hull the vertical stresses and three guides that did the same with the transversals. Each bolt had a sensor at the end of its path, so in the bridge a collection of green lights; unfortunately, a door may be pulled off its frame (by force) without unlocking the bolt.

There were also something inherently flawed: to begin, the interior closing limited by the ramp was considered an extension of the collision bulkhead, but since its distance to the prow was less than specified at the SOLAS Convention, in theory the ship could not go farther than 20 nm off the coast, a limitation that, in fact, was not applicable at the Baltic. Also, hoisted and closed the ramp protruded 1,20 m over the forecastle, being accommodated at a protuberance of the "movable prow" or "peak"

when sailing: this was not optimal since if the peak was pulled off position (something not easily imaginable), the ramp also suffered (see the image).

Finally, even if a weight of 56 tons may seem to keep in its place a peak that opens upwards, it displaced 165 cubic meters of water (completely submerged, so with heavy sea). Also, in the design, the bridgewas moved 11 m from the initial plan *"to give the vessel a better silhouette"*, so the prow was hidden to the conning officer.

The situation that lead to the disaster can be maybe traced to 1989, when, encouraged with the "Perestroika" the national Swedish Naval Company Nordström&Tullin (N&T) decided to cross "Iron Curtain" with a regular line Stockholm-Tallinn. They made it in 1990 with a mixed company (N&T Estline AB) and a Swedish ferry ("Nord Estonia") but, according to GGOE, in 1992 it was taken the decision to *"replace the Swedish flag/Swedish crew "Nord Estonia" by a larger but cheaper ferry"*, problem solved with an old ship: *"Viking Sally" was picked out to be the successor,* with a new name: Estonia (*"…under Estonian flag with Estonian crew"*). It is possible that in 1993 and at Stockholm, the "Estonia" was an obsolete ferry, but moored at Tallinn with the Estonian flag would be a motive of pride for the Estonians (that did not know all the complex details). Resuming, since in 1992 the Estonian register was not acceptable by the banks, the ferry was registered at Cyprus. On this base, the ship could be rented as a "bareboat charter" to another Estonian-Swedish company (the E-Line, property of ESCO and N&T), inscribe itself in a special register and, finally, hoist the Estonian flag at the poop, which allowed E-Line to contract to ESCO an Estonian crew and ESCO to subcontract to N&T the more technical aspects. Capitalism in Estonia was blooming.

The new service between the capitals of Estonia and Sweden was launched 1st February, 1993: every two days the ferry parted from Tallinn over 1900 and reached Stockholm 0900 the following day, sailing again at 1730 to end in Tallinn towards 0900. Till then "Estonia" had traveled only at relatively sheltered waters, but now it faced transits of 225 miles, 140 of them at open waters with waves of a significant wave height of 3.1 m 10% of the time. The time schedule required an average speed of 16.5 knots in open waters, two and a half less than the maximum of service. Even though the time in port could absorb delays, for the Estonians delay was not an option. In this aspect they were different from Swedes or Finns, who with bad weather reduced the velocity allowing the passage to spend its money aboard with more calm. Hurries at last would be fatal to an "old" prow that had never been a masterpiece: GGOE provided information that, besides not carrying out the reparations scheduled for 1993, the following winter seas and ice gave such a beating to the "peak" that in the middle of 1994, it was misaligned and navigated partially inundated. Relating the ramp, GGOE points that at some moment of 1994, a hinge was bended and it was each time more difficult to place in its frame, requiring its "reopening" great distress; it is almost sure she navigated not properly closed, and the crew used rags to improve its "seal". On 27th September, 1994 the "Estonia" was moored at Tallinn and for its young and novice 1st Officer, Juhan Herma, it was hard time, since, besides a complete carriage of vehicles and with heavy sea in perspective, there were nine future Estonian Inspectors of Maritime Security and its two Swedish instructors, that were from 1200 till 1730 asking questions. Their most relevant "finding" was water tightness was not considered a critical point. However, they did not "reflect" that the loading the ship, which is a responsibility of the First Officer, had begun more than an hour ago. The loading was a little sloppy with the heaviest vehicles at what would be the leeward side, and the ballast tank of the opposite side full.
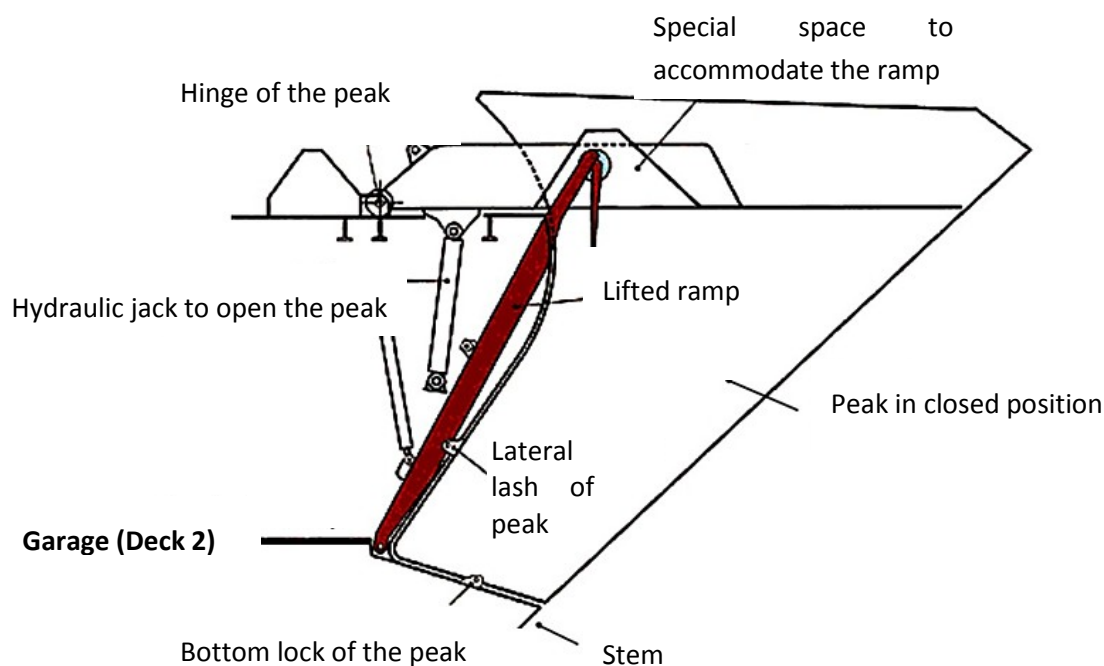
**Figure 29**: Configuration of the prow of MV Estonia in navigation (from Jar Torre, 2008).

MV Estonia had two complete crews that turned every fourteen days, and that was the thirteenth of the crew commanded by Arvo Andresson. Andresson had finished his studies at Leningrad, navigating from 1974 with the sickle and the hammer at the chimney and becoming the "apparatchik" who launched the ship and received the first official title of Master Mariner of Estonia. In comparison, Herma completed a month of 1st. Officer and six navigating, and the rest of the bridge officers an average of three.

The N&T had tried to have Swedish captains and first officers but because of Estonian opposition, they embarked as "as nautical assessors", captains experts in that type of ships and with Pilot License for both access canals to Stockholm, that initially the Estonians did not have. That trip Andresson had both licenses, and precisely, he was joined aboard by the captain of the Alternative crew, Avo Piht, that was going to take the exam next day for the N canal (Söderarm). If we are to believe GGOE, the relation between Estonian officers and Swedish assessors was not very good: Andresson did not get the hold on the maneuvers, and in an authoritarian environment, not even the 1st. Officer dared to get close to the tele-commands.

The forecast received that 27th September should have brought some worry: at night a deep depression would displace from the S of Norway to S of Finland, causing at the zone winds from SW of force 8 shifting to NW to 9/10 Beaufort, rain and waves some 3 m of Significant Height and 5.5 m of Maximum Height (Hm≈1.8·Hs) in open water. It seems the real waves were even somewhat higher, but if we have to judge from the reports, the main concern were the possible delays.

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Around 2200 the "Estonia" left by board the island of Osmussaar: it navigated to 262/vº, heeling a minimum of 2º to starboard while the wind began to shift towards board and the sea worsened: at 2300 there was SW Force 7 and waves of more than 3 m.. The commands would continue set for the maximum service speed, but as the sea worsened also the pitch did: around 2320 the ferry crossed at a mile and a half with the Polish roro "Amber", whose officer recalled perfectly seeing it navigate full ahead against the sea, brightly illuminated... and with waves that embarked at its forecastle, splashing till the bridge. The Moon had risen at 2150 and the scene must have been remarkable. The Polish reflected its "impressions" for the GGOE ("*In my opinion those in charge on the bridge of the "Estonia" must have been crazy, absolutely incompetent and inexperienced*"); in any case, the show must have been something to remember ("*I had never seen anything like this before*"). Aboard "Estonia", the slamming of the waves were heard at least from 2300 and the Speed Over Ground had been decreasing to some 16 knots, but when captain Andresson appeared again soon before midnight, he only checked that the four engines worked, and before retiring again towards 0010, he commanded that at the next change of course (waypoint), the stabilizers be activated. The idea was to continue to 262/vº fifteen more minutes (to 59º20´N 22º00E) and then turn 25º to starboard, prow to the canal of Söderarm some 85 miles from the prow, which would leave the open sea some 30º by board. By then the wind was SW Force 8 and the sea came almost from prow, with waves of Hs almost 4 m and maximum between 6 and 8 m: JAIC estimated that, in her life, the ship would have been exposed to such waves less than twenty hours and, observing the documentation of the GGOE, rarely full ahead.

The report of the GGOE had a declaration of the bosses of the Captain (*"Estonia had to maintain her arrival at Stockholm by all means and that this had been made quite clear to the masters"*) and another one from a passenger that took supper near captain's table (*"During one of these "wave bangs" the master sitting next to the witnesses stiffened. This was clearly visible, especially on the face of the master.*"). There is another declaration of Einar Kukk, an officer with experience sent there to absorb "knowledge" at the flagship of the company. Kukk would be the only surviving bridge officer:*"…officers on watch were frightened about the much too high speed, but did not dare to reduce the pitch without instructions from the master"*. Around 0025 the conning officer changed the course as planned to 287º giro and activated the stabilizers, commenting to Kukk that with them the speed would decrease even more; soon after, Kukk finished his guard at the bridge almost at the same time as the seaman Silver Linde, who began its roundabout. In some moment after 0045 and while he was it the garage near the prow ramp, Linde experimented a heavy vertical acceleration that almost made him fall and, simultaneously, heard a *"sharp metallic bang"* from the prow he communicated to the bridge, received the order to investigate its origin till, after five minutes without any other novelty, he was authorized to continue his roundabout. Around 0100 and while the 2nd Officer "A" and the 4th Officer replaced the 2nd Officer "B" and the 3rd Officer, Linde went back to the bridge meeting at the door Captain Andresson, who noted the heavy rolling and that, *"in spite of having all engines running"*, they were an hour late: really, an hour was more than most of the persons on board were to live.

**Figure 30:** Photo of MV Estonia when it was still the Wasa King, made at Sundsvall (Sweden) between 1991 and 1992. The peak or visor may be observed in the open position and the hinges seem indeed delicate. The open ramp where the water flooded in may also be observed. Photo by Jaana Seppelin from the article of Jar Torre (2008).

It is possible that the sound reported by Linde was the breaking of the board latch of the visor: from that moment, the other two latches would bear additional stresses until they broke and left the peak or visor fixed to the hull only by the hinges and the hydraulic jacks. The hinges were designed to bear vertical loads of hundreds of tons but, due to the horizontal forces its robust anchorage began to tear apart the deck of the forecastle, the entire ensemble began to move towards prow pushing the ramp till ripping it of its precarious lashings and leaving it semi-open and leaning at the visor. Evidently it was a noisy process and the alarmed passage the bridge: around 0108 the 2$^{nd}$ "A" Official ordered the Seaman to investigate again, now with the Boatswain. After seven minutes Linde still waited the doors of the garage to be opened, while the captain, who was at the bridge, continued full ahead. Around 0115 the last connection of the visor broke and, before sinking at the Baltic, its 56 tons hit the bulb with a force that could be heard all around the ship. The ramp completely opened (lost its support) and the sea entered tumultuously at the garage; some two minutes later, the ship listed some 15º to starboard.

At the bridge they had their own problems and because of the listing, that, increasing minute after minute, was turning the space in a well 27 m deep; at 0122, the 2nd "A" Officer reached one of the six VHF terminals (or maybe a portable) and, in an apparent state of "shock", transmitted an irregular SOS ("Mayday Mayday Estonia please"). The nearest ships were the two ferries that covered the route Helsinki-Stockholm: the "Silja Europa" (Silja Line), some 11 miles and "Mariella" (Viking Line), at also at some 11; the captain of "Mariella" had reduced the speed to some 12 knots around 2300, andthe conning officer of the "Silja Europa" had done the same. Both answered the mayday, but the stressed 2ond Officer "A" continued to send inconsistent calls until at 0124 the 3rd Officer Andres Tammes (free on watch), made contact withthe 1st Officer of "Silja Europa" (*"Good morning, do you speak Finnish?"*): Tammes had studied nautical science at Finland, and his Finnish mate navigated at the "Estonia", when it was called "Wasa King". Around 0125, due to listing, the sea began to break the windows of decks 4&5, whose inundation destroyed the last reserves of stability; when (around 0125) reached 45º less thana third part of the passengers and crew had reached the exterior and the rest was condemned. The first alarm was an atypical message in Estonian by a weak female voice through the public address system (loudspeakers): "*Häire, häire, laeval on häire*"("Alarm, alarm, there is alarm on the ship") around 0119. Around 0120 the bridge emitted, also by public address system, a "ciphered" message (*"Mr Skylight to number one and two"*) that reallymeant that the two fire-fighting groups must gather without alarming the passage. Two minutes later the signal of "abandoning the ship" (seven short blasts and one long) but, since they had set the l side to windward with force 9 winds and very heavy sea, to abandon the ship from starboard was now suicidal, and from board a work of acrobats.

From the bridge of the "Mariella", they saw how the lights of "Estonia" went off, and, at four miles, how its eco extinguished from the radar around 0153; when they arrived, the lights of the rafts seemed a fallen Christmas tree to his Master. The gale prevented lifeboats from being lowered and,while the helicopters arrived, they had to throw life jackets and rafts to the sea; the transcriptions of VHF shows a sad agreement with "Silja Europa" (0220: *"Yes, that is the only possibility, I am of the opinion that the weather is so severe" // "Yes, I am of the same opinion too" // "Yes, that is good"*). For the Master of the "Mariella" it was a situation difficult to stand (0232: *"...the sea is full of people round us..."*). He rescued some 15 persons from the rafts of the "Estonia" lowering and hoistingits own rafts with the crane (ferry "Isabella" would rescue other 16 ¡with an inflatable ramp!). Thefirsthelicopterarrivedat 0305 and in the next 15 hours other 25 joined (and 29 boats), butthewaterwas at some 10ºCand when, around 0900, the last survivorwas rescued,they only added 138 (one would diea little later); from a total of 852 victims only 92 bodies could be recovered. The JAIC concluded that thedesign of the visor of the "*Estonia*" didnot contemplate realistic loads and had scarce margin of security, which reinforces the idea that it would have been treated more properly. So mechanical failure was the main cause of this catastrophe, but the hurries and the inexperience of the Estonians in handling this type of ship also played a role. After being the last ferry in abandoning the zone, the brave "*Silja Europa*" arrived the next day to Stockholm with such malfunctions at its prow that the port door could not be opened. Casually, at 1985 the "*Mariella*" had suffered faults even more graves at its visor, and the JAIC registered similar incidents or even worse in other eleven Baltic ferries. The visor of "*Estonia*" was recuperated and studied, so now we may travel with ferry with total safety; however, after discussions, it was decided that the "Estonia" and its occupants be leftat 59º22,9N and 21º41,0E, a sanctuary at a depth of 80 m.

So with all this information we are able to draw a "tree of events". An effort of synthesis must be made in making the tree. It must be stated that maybe this catastrophe had to occur, as is pointed in Jar Torre (2006) in the title of his article. The ship was almost 15 years old when it sank, so it is not extremely old and it could have continued at the sea some more years. It is normal, however, that the final blow to the ship occurs in heavy weather. It may be observed that the reserves of stability at a ferry are not those of a passenger ship and the disaster occurred very quickly (and maybe quicker due to the bad decisions at the bridge, in this case attributable to the Master since there was, seems, an authoritarian discipline heir to the Soviet times).

Other famous cases of ships that have suffered a mechanical failure caused by heavy weather causing its sinking are the tankers Erika (1999) and Prestige (2002), which is the last large tanker lost at sea to this day.

What is clear is that the best barrier or way to have prevented the accident would have been the exhaustive control of the ship. The malfunction of the "visor" should have been repaired.

The casualties "had an immense impact on the world concept of ferry safety" and led to changes in safety regulations as well as in liferaft design[15],much as the Titanicdisaster did in 1912. The EPIRBs or radio beacon distress indicators were required from then to deploy automatically and the accident was instrumental in the move to legislate Voyage Data Recorders (VDR)".

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[15]Joughin, R.W. "The Revised SOLAS Regulations for Ro-Ro Ferries". Warsah Maritime Centre. Archived from the original on 3 April 2008. Retrieved 3 April 2008

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**Estonia**:

The flagship of an Estonian public company (also with Swedish public participation, N&T).

A country that had done (or was still doing) a transition to capitalism and did not spend all the money necessary in revisions.

Also, the company had a priority with the "time schedule" and since it was the only ship on the route, it could not be "turned out"

**The crew:**

That day there was an important representation of crew A, members (from the other crew) and Swedish assessors. This had no great importance since the Master ruled the navigation.

An experienced Master, but according to the reports, with scarce imagination. He had been on the line since the beginning of this route

**The gale:**

Not an unusual gale for the Baltic. The height and period of the waves is not known "a priori", but the waves reached the forecastle.

It must be noted that this ferry was not designed to navigate open waters, since the design of the prow

**Mechanical failure:**

When the stresses cause one of the three locks to blow, the other two do not resist long. The hinges at the deck are ripen soon after and the "visor" is lost.

Immediately the ramp opens to the sea, embarking tons of water to the garage

The crew is overwhelmed with the magnitude of the disaster. Radio distress communications with the passengers and other ships are not "standard".

Unfortunately the freezing temperatures of the water do not allow survival for much time. Many passengers are also not able to reach the deck.

A great majority of officers and crew members die, some heroically, setting out the life rafts. Which was difficult due to the list of the ship.

There is no time of reaction.

852 victims and 137 rescued.

The design of the ferries has been improved.

The design of the visors has been enhanced since the time of the catastrophe.

Estonia has become a fully integrated country in the UE.

From that date, 1994, not another SOLAS ferry has sunk (up to 2016), except the South Korean Sewol, in 2014, with 304 victims.
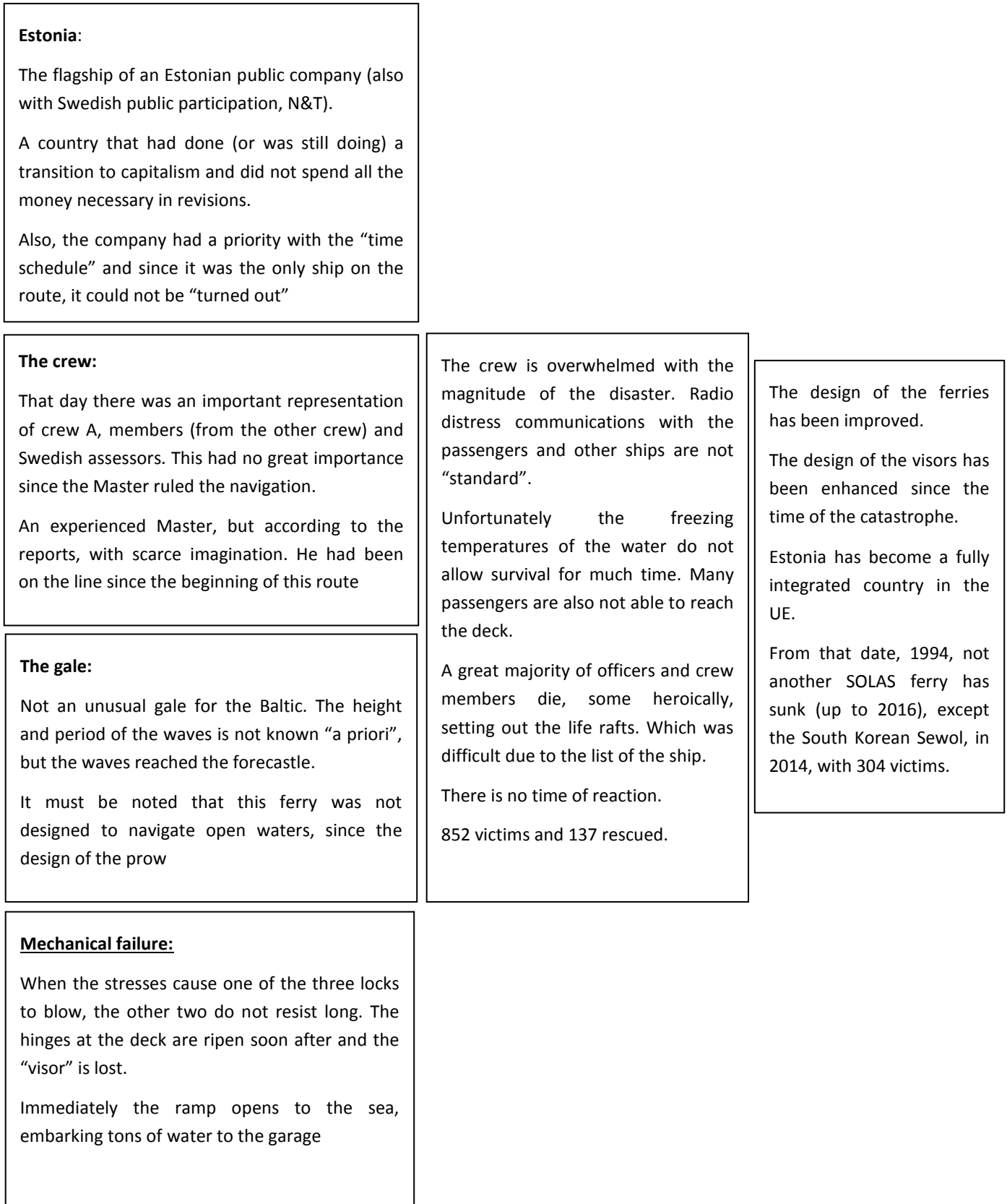
**Figure 31**: Conceptual "Bowtie Model" of the disaster of MV Estonia, with the causal factors at the left and the consequences at the right. No probabilities are given.

**Control of ships, safety, anti-pollution standards and methods of enforcement**

Any discussion on methods for the enforcement of maritime standards must begin with some reference to the volume and complexity of regulatory requirements generated by the various international conventions in force. The Load Line Convention of 1966 is a relatively simple instrument and one hopes it will remain so.

**Port State Control and the European Memorandum of Understanding**

The origins of port state control lie in the memorandum of understanding between certain eight North Sea States that was signed at The Hague during 1978. This collective agreement was for the inspection of shipping of all flags that entered the ports of the member States.

Although this agreement was perhaps a little slow to get off the ground, it did at once show itself to be both desirable and effective dealing with the sub-standard ship. The result was a European conference of ministers on maritime safety, giving birth to the memorandum of understanding (MOU) signed in Paris between 14 member States

A great deal depends upon the method of selection of vessels for PSC inspection. Systems vary not only from one member country to another, but also from one geographical area to another within the countries. The underlying themes, however, are that no vessel is normally inspected more frequently than six months after the last inspection or certificate renewal.

A number of factors generally govern the final selection of ships that might be inspected at any given time, and these might be seen to include age, track record and a vessel which may involve a special hazard, such as an oil, chemical or gas tanker. When the surveyor boards a vessel for PSC he is not biased in any way, but will be acting purely as his own professional judgement dictates, and one of three situations develop:

a) Certificates all in order and the surveyor has no misgivings concerning the condition of the vessel.
b) Certificates invalid or missing
c) Certificates all in order but, the surveyor decides there are clear grounds for believing that the condition of the vessel

The first case of everything in order clearly requires no further attention. The other two, however, require some consideration which will depend entirely upon the severity of the deficiencies and the intended voyage, but will, sooner or later, culminate in the surveyor being satisfied with the vessel's condition. If the surveyor's satisfaction is only partial when the vessel is ready to sail, he may, at his discretion, communicate with the maritime authority of the next port of call if it is within a Paris agreement State,

The whole concept of MOU is for the surveyor to look first at the ship's certificates, and it is only when these are defective in some way

A ship detained is of considerable concern. The instrument of detention is a piece of paper. For detention, a ship is not physically restrained, but the penalty for breaking detention is substantial, quite apart from penalties associated with taking or sending an unsafe vessel to sea. Physical restriction of a vessel is usually associated with arrest, and achieved by immobilizing the vessel concerned.

One must not confuse arrest with detention. Arrest is associated with legal proceedings against a ship, often for non-payment of bills, and the actual arrest follows a Court order. Surveyors are not associated with arrest.

It is important to mention that ship detention is not the only sanction available, but is the one often associated with MOU matters and unsafe ships. It may be regarded as an instant penalty, and of course there are procedures for those who feel detention has been improperly applied, including the recovery from the marine administration of sums of money to defray the losses involved with wrongful detention.

## 4.4. Security (Piracy and Terrorism)

### 4.4.1. Piracy

"*Whosoever, in an attempt to commit the crime of piracy, in respect of any ship or vessel, shall assault it with the intent to murder any person on board, or shall wound any person, or unlawfully do any act by which the life of such person may be endangered, shall be guilty of felony, and being convicted thereof, shall suffer death…*". This is an extract from the Piracy Act, a law of the United Kingdom to prevent piracy (in its version of 1837).

This legislation in the United Kingdom to prevent Piracy would be a "barrier" in a bowtie model thus. It shows that the British took very seriously the attacks at ships (and they still do as all the countries). Only in 1998 the mandatory death penalty was abolished, and the sentence is now up to life imprisonment.

However, there are armies and crews that, claiming maybe the right of auto-defense, shoot and sinks pirate ships, as may be seen in many videos[16].

Piracy had remained forgotten until the early 1980´s. Even when it became noticeable it was from sporadic incidents confined to a few parts of the west Coast of Africa and Southeast Asia.

Pirates come from diverse backgrounds, from disorganized bands with knives as their most offensive weapon to uniform-clad thugs carrying automatic arms.

They show familiarity with ships, suggesting experience at sea, and various methods they use, although they vary in detail, are basically the same. The preference for darkness is evident from records, which show that most incursions have occurred between 2200 and 0400 hours.

To infuse purpose into actions and thoroughness in security it is essential that members of the crew understand the priorities well and plan ahead as they do for any other emergency.

The danger that pirates pose to a crew is obvious from the record of fatalities. Numerous seamen have lost their lives in these hostile assaults.

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[16]See, e.g. https://www.youtube.com/watch?v=4XJ0nblZjZE. There is plenty footage at youtube of pirates being captured also. The most expeditious Navies are the Russian and the Chinese, maybe.

The object is early detection of criminals and prevention by discouraging boarding. It is not resistance once armed criminals are on board.

### 4.4.2. Terrorism

According to UNCLOS (International Law of Seas, Article 101) Piracy consists of any of the following acts, so terrorism would be included in piracy:

"(*a*) *any illegal acts of violence or detention, or any act of depredation, committed for private ends by the crew or the passengers of a private ship or a private aircraft, and directed:*

*(i) on the high seas, against another ship or aircraft, or against persons or property on board such ship or aircraft;*

*(ii) against a ship, aircraft, persons or property in a place outside the jurisdiction of any State;*

*(b) any act of voluntary participation in the operation of a ship or of an aircraft with knowledge of facts making it a pirate ship or aircraft;*

*(c) any act of inciting or of intentionally facilitating an act described in subparagraph (a) or (b).*"

The difference between piracy and terrorism is that their motivation is that the motivation of pirates is mainly economical and that of terrorists political although the border between both may be diffuse, evidently.

The greatest advantage that terrorists have and will continue to have is a virtually unlimited range of targets. Terrorists can attack anything, anywhere, anytime, limited only by operational considerations: terrorists do not attack defended targets; they seek soft targets. If one target or set of targets is well protected, terrorists merely shift their sights to other targets that are not so well protected. After the terrorist attacks of 11S, the airports have included better security measures and thus it is natural that ships and port facilities try to also increase also the security. It may be observed that a place where it is very difficult to set security measures, the Metro and proximity train system, has been attacked heavily at Madrid (2004) and London (2005).

Fortunately, terrorist attacks at ships have been relatively halted these last years if we consider the chronology of accidents from years 1960-1983.

We are going to make a little resume to see the different typologies of coups.

In 1960, In Port of Spain, Trinidad, oil company workers on strike against Texaco Trinidad Inc., opened storage tank valves, spilling 200,000 gallons of gasoline, kerosene and oil into the sea.

The first modern hijack at sea was in 1961 and lasted 11 days. At the Caribbean, the 21,000 ton Portuguese liner Santa María was seized at sea by a group of 70 men, led by Captain Henrique Galvao, a Portuguese political exile and a leading opponent of Dr. Salazar's government. The liner was on holiday cruise with over 600 Portuguese, American, Dutch, Venezuelan and Spanish passengers on board, among them many women and children. The takeover of the ship occurred at 1:30 when a group among the passengers, armed with machine guns and hand grenades, assaulted the bridge of the ship, killing the Third Officer who was on watch and resisted the assault, and injuring three other crew members.

An international search involving ships from many navies was mounted to locate the Santa María which was spotted eventually by a US naval plane and persuaded to alter course for Recife.

Attempts to define terrorism comprehensively have not met with a great deal of success, since some terrorists may consider themselves at war. This holds particularly true for terrorism in the maritime element.

The definition used is usually then, could be: Maritime terrorism=Attacks on ships or maritime installations by non-governmental groupings for reasons other than immediate financial gain. In this way, piracy is not included, nor attacks that take place during war.

Three quarters of the incidents that occurred between 1961 and 1970 are attributed to anti-Castro exile groups. Some of these groups received initial training from CIA. These groups presumably turned to maritime terrorism as a result of their failure to establish themselves on the Cuban mainland. All the attacks took place after the Bay of Pigs invasion fiasco (1961). The only way they could continue their "war" was in the marine element.The last registered case is in 1977, when attempts to attack Cuban patrol boats (Cuban Navy) by CORU, an anti-Castro group, were prevalent during the summer of that year.

The provisional wing of the Irish Republican Army has occasionally carried out attacks on maritime targets. The first incident was in February 1972, when a bomb was discovered on the Duke of Argyle, a passenger ferry.

The Polisario Front, which is currently fighting Morocco, has been among the most active and successful practitioners of maritime terrorism. Polisario is credited with at least 17 attacks since 1978. The usual modus operandi is to attack fishing boats off the coast of what it claims is the Saharan Arab Democratic Republic. It uses Zodiac-type motorized rafts, and usually machine-guns or fires light missiles. On a number of occasions, the stricken vessel has been boarded, the crew removed and held for ransom.

So we have seen that the maritime world, the majority of which belongs to international waters, has been traditionally characterized by a lack of control, bordering the anarchy. Traditionally, it has been an ideal environment for transnational crime such as piracy and terrorism. Theattacks to USS COLE in 2000 and to MV Limburg in 2002, with speedboats loaded with explosives, by the organization al-Qaeda, showed these terrorists had the capacity to attack at the sea.
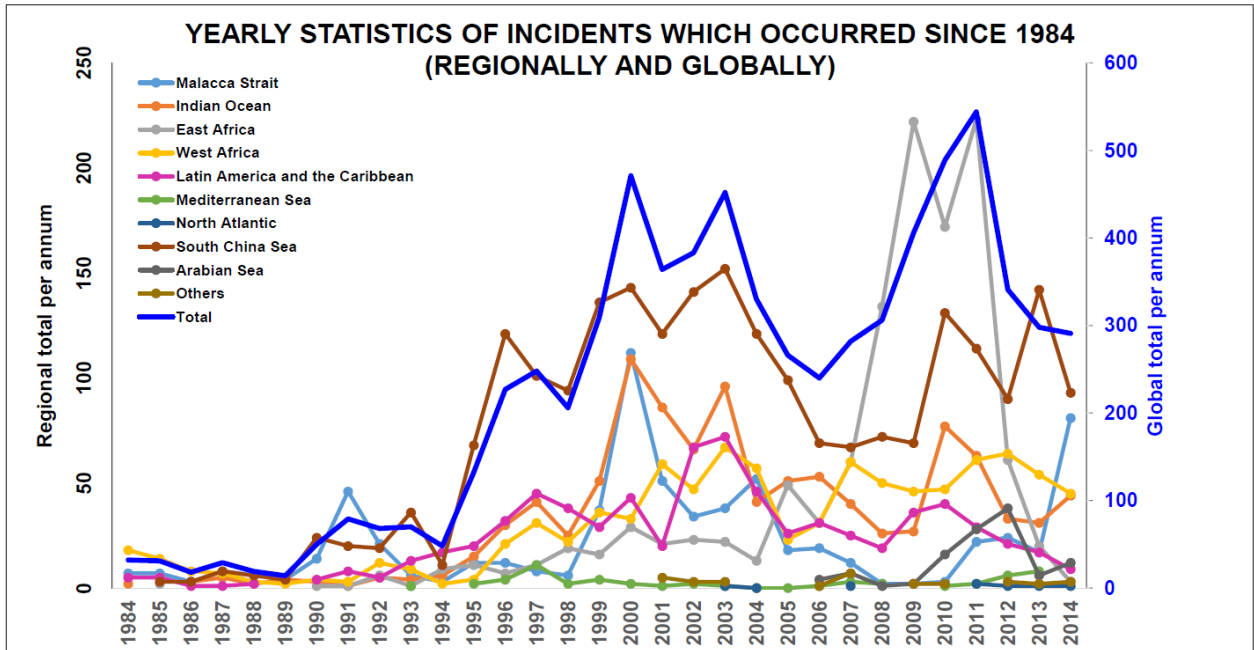
**Figure 32**: Yearly statistics of piracy and terrorism incidents. The great majority are piracy. It can be observed that there was a peak in 2011 but now it has been cut to almost half, globally, although there are some areas where it is increasing, like the Malacca Strait. Figure from the annual report 2014 of the IMO on piracy (http://www.imo.org/en/OurWork/Security/PiracyArmedRobbery/Reports/Documents/219_Annual_2014.pdf).

### 4.4.3. The IMO and maritime protection. The ISPS code.

The juridical regime of security, understood as a protection of persons and goods for the international maritime transport, came into effort July, 1$^{st}$, 2004. Its adoption was a result of the diplomatic conference of December, 2002, where IMO established a series of measures to strengthen maritime protection of the ships and port installations, and to prevent terrorist acts. This conference adopted various amends to the SOLAS Convention 1974, of which the one with the farthest reach is the tie with the International Code for the Ship and Port Facility Security (ISPS).

The dispositions are at chapter IX of SOLAS, which is subdivided in 2 parts. At the first the amends at SOLAS are presented, while at the second it is obligatory to adopt the new ISPS code. This Code recognizes terrorism as the main menace on the maritime transport (after the wake of the terrible attacks of 11-September-2001 at the USA. From the beginning of this process, it was clear that the point of reference and main responsibility of these security measures would be the States. In the context of the PBIP there are cited directly and constantly the functions of the "contracting States". The initiation and the maintenance of the processes and necessary procedures begin and end with the national governments members of the IMO.

The part A of the Code is mainly against terrorism. Part A contains the obligatory dispositions while B contains "recommended" dispositions.

The EU issued the Regulation (CE) 725/2004 of the Parliament and the Counsel, from 31 March 2004, relative to enhancing the protection of the ships and port installations.Before the prescriptions of the ISPS code, the companies had to keep similar security levels as the port where they are hosted.

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**Ship protection systems, AIS and LRIT**

Although they are not specifically contemplated at the ISPS Code, the SOLAS Convention does. In it, the Conference of the Contracting Governments agreed to modify the chapter referring to the Automatic Identification System or AIS. This system allows to transmit from a ship, coastal stations or airplanes, a series of significant data on the ship, whether it is in navigation or moored, its situation, course, and other data that affect its protection.

The use of AIS (obligatory since 2004), had initially 2 serious problems: it emitted openly and its range was very similar to that of VHF. So this changes with the configuration of the Long Range system of Identification and Tracking (LRIT), whose main characteristics are: Codified Information, by satellite and reserved (only for authorities and public administrations). LRIT System must be able to extend the survey of marine traffic to all the sea. Each state must be capable of obtaining automatically the actualized positions of its ships every 6 hours (4 daily contacts).

On the other hand, all the ships affected by the ISPS Code must have an alert system for protection, which must transmit a signal when the ship is hijacked by pirates, attacked by terrorists, etc. It alerts the flag state that it is being affected by something concerning maritime security. It does not generate any alarm on board (visual or acoustic), so it keeps the attackers from knowing the alert has been activated. The information transmitted includes the coordinates and identification of the ship.

**The reality of the Implementation of the ISPS Code**

Even though the introduction of the ISPS code, the increase in the perception of danger and all the regulations and tools to aid sea-borne companies in their efforts to maintain a safe environment, it must be recognized that in many occasions it has not the necessary priority in the naval industry.

So, what may be improved? It is important to understand that the reason of the implementation of the ISPS code being relatively simple and quick was that it was not very exigent. ISPS provides a frame but does not stipulatespecific standards.  Ships and ports must have security plans, security officers and some security equipment, but it is left to each government to specify. For example, the ISPS (to date) does not establish a minimum standard of formation to be a "qualified" security officer. On the other hand, ISPS is only applicable to SOLAS ships.

# 5. Chain of errors.

So, we have observed in the previous chapter that (except in the case of piracy and terrorosm, where the cause is clear), maritime incidents or disasters are very seldom the result of a single event, they are almost invariably the result of a series of non-serious incidents; the culmination of an error chain. Like in our everyday life, when something adverse occurs we have usually have had a "near miss" before. An example could be losing the wallet: probably before it actually happens, surely we have almost lost it before but because of chance, it has been recovered. If we are keen enough to change our habits, we will probably elude finally losing the wallet (that after it happens, we will find that it was totally probable).But sometimes this is not so easy to do (we may be stressed). After something adverse has happened to us (evidently, if it is something we have some control on), it is easy to trace back the things we have done recklessly. So we could say, as Oscar Wilde, that experience is the name we give to our errors.

So situational awareness (this state that is not so easy to achieve when all is under control and we have an inner equilibrium) helps the OOW recognize that an error chain is developing and taking such action, based upon this awareness, to break the error chain.

## 5.1. INDICATIONS OF ERROR CHAIN DEVELOPMENT

According to the Practical Guide of Bridge Team Management, by Capt. A J Swift (1993), certain signs in the function of a bridge team will indicate that an error chain is developing. This does not mean that an incident is about to happen; it means that the passage is not being carried out as planned and that certain elements of situational awareness are missing. Action must be taken to break the error chain.

**Ambiguity**: There are indications that things are not going as expected. In the event that two independent and separate position fixing systems –e.g., radar fix and GPS positions- do not agree, obviously something must be wrong with one of the systems. A variation may be that the echo-sounder reading does not agree with the chartered depth.

Ambiguity may exist in that two members of the team do not agree upon a point of action. Ambiguity exists

Ambiguity may be a result of experience and lack of training. The junior officer may feel he is not in a position to voice his doubts. This should not be the case, since, as we have been told, people are normally prone and proud to teach others. Every member of a well-constructed, well-briefed team will be confident that his doubts or fears can be expressed without his being reprimanded for what may turn out to be a very pertinent and saving remark.

**Distraction:**

Distraction can be caused by an excessive workload, stress or fatigue, emergency conditions or, all too often, inattention to detail. It may also be caused by an unexpected, though not threatening event, such as a phone call. This is precisely the case of the tragic accident of a derailment of a high-speed train that occurred at Santiago de Compostela, Spain, the 24th July, 2013, when the driver of the train received a call from RENFE (Spanish Rail) staff that was also inside the train, for a trivial consult (without impeding the safety measures of the track being always improvable). At the sea it is also possible to receive VHF calls, and nowadays we are able to receive some mobile phone calls near the coast, where the situation is more dangerous since we are near land (and there are also satellite telephones).

**Inadequacy and confusion**

This is a less definable indication of situational awareness where the person concerned has the feeling that he islosing control of the situation. The person concerned does not know what is expected to happen next. For example, position fixing is not going as it should.

**Communication breakdown**

Poor communications, both external and internal, are an indication that situational awareness may be at risk. Internal communications may be confused by physical causes such as noise, etc…or be caused by lack of common language or differing procedural methods. In any case, efforts must be done to overcome the cause of the communication breakdown, otherwise teamwork and mutual knowledge is at risk.

**Improper conn or lookout**

Improper conning or poor lookout may be a result of lack of situational awareness as well as an indication of its breakdown. Within the bridge team organization the most important aspect is a safe conn and breakdown of this situation may lead to the ship being hazarded.

**Noncompliance with plan**

Non-compliance with the passage plan may result from the improper conn noted above, and is another indication that the situational awareness is breaking down.

**Procedural violation**

Unjustified departure from clearly defined and understood operating procedures must be recognized as a breakdown of situation awareness. As an example, the OOW of a ship which is proceeding in the wrong lane of a Traffic Separation Scheme must ask himself why he is doing this. It is a direct violation of the International Regulations for Preventing Collisions at Sea.

According to the International Safety Conference (INTASAFCON III) held in Norway it was agreed that the main principal factors that seem to be the main cause of collision and groundings are:

*Weaknesses in bridge organization and, as a result of such weaknesses, failure to keep a good lookout*. Such casualties may have been avoided by:

**Setting double watches in appropriate circumstances:** Too often it is considered adequate to continue in a more complex situation with the same bridge manning levels as if the ship were deep sea with less immediate potential hazards.

**Ensuring sufficient personnel are available in special circumstances:** Additional personnel are often required to prepare equipment or to be available under certain circumstances. If calling them is left too late they may not become available until the ship is in the situation they could have helped prevent.

**Precise instructions for calling the Master:** Too often the Master is called after a situation has irredeemably deteriorated. If the OOW is unclear as to when he should call the Master then his indecision may lead to his not calling the Master

**An established drill for changing over from automatic to manual steering**: Despite the ease with which modern steering gear can be changed from one system to another, major incidents are on record where lack of awareness of the precise steering system in operation has led to disaster

The following features have been noticeable as causes of groundings:

**Failure to pre-plan a track:** Frequently it is not considered necessary to plan a track and show it on the chart. This may be because the mariners concerned feel that they know the area sufficiently well or because there is a pilot on the bridge.

**Failure to monitor adequately the vessel's progress along the planned track**: Although a planned track is shown on the chart OOWs do not always constantly and regularly fix the ship. This may lead to the OOW not being aware that the ship is deviating from the track, perhaps towards danger.

**Failure to take immediate action to regain track having deviated from it:** Even when aware that deviation from the track is occurring, the attitude may be that it doesn't really matter, when this is not actually the case.

**Failure to cross-check fixes by comparing one means with another:** If only one method of fixing is used when the ship is in constrained waters, misidentification of a navigation mark or faulty electronic information, left unchecked and unobserved, may leave the OOW with a false sense of security.

**Failure to use the echo-sounder when making a landfall or navigating in constrained waters**: Except when alongside, the ship's nearest danger is almost invariably below. Although it cannot be considered to be a position fix, observation and appreciation of the under-keel clearance can often warn the observer of approaching danger or that the ship is not in the position that it should be.

**Failure to identify correctly navigational lights**: An observer may convince himself that he sees the light he is looking for

Failure to ensure that important navigational decisions are independently checked by another officer: By their very nature all human beings are likely to make errors.

An efficient bridge organization will include procedures that:

1. Eliminate the risk that an error on the part of one person may result in a disastrous situation.
2. Emphasize the necessity to maintain a good visual lookout and to carry out collision avoidance routines.
3. Encourage the use of all means of establishing the ship's position so that in the case of one method becoming unreliable others are immediately available.

These procedures can only be achieved by each member of the bridge team realizing that he has a vital part to play in the safe navigation of the ship and that he has a

5. Chain of errors.

**Navigating with a pilot on board**

The relationship between the ship's team and an employed pilot is difficult to define.

The ship's Master is charged with the responsibility for the safety of the ship; pilots are engaged to assist with navigation in confined waters and to facilitate port approach, berthing and departure. The Master has the ultimate responsibility and has the right to take over from the pilot in the rare event of the Pilot's inexperience or misjudgment. In practice, the Master may find himself in a position where he is not happy about the way the passage is being conducted by the pilot, yet is in no position

Ideally, the Master and his team will be aware of the pilot's intentions and be in a position to be able to query his actions at any stage of the passage

1) The bridge team being aware of the difficulties and constraints of the pilotage area.
2) The pilot being aware of the characteristics of the ship.
3) The pilot being familiar with the equipment at his disposal and aware of the degree of support he can expect from the ship's personnel.

Such insecurities and doubts can quite easily be overcome by the ship's team operating a consistent system.

Planning: A well planned passage will not stop at the pilot boarding area. The planning will continue from sea to berth, or vice versa, the boardingof the pilot being part of the plan. The areas where the pilot actually has the conn will still have been planned by the navigator. This enables the Master and OOW to compare the progress of the ship with the planned track and also enables them to be aware of the constraints and other details of the passage.

Master/Pilot information exchange: As stated, the Master may not be aware of the area, the pilot is unaware of the peculiarities of the ship. These problems can be minimized by establishing a routine Master/Pilot exchange. When the pilot enters the bridge it is a good practice for the Master to make time for a brief discussion with the pilot. The Master may need to delegate the conn to the OOW or other officer, as appropriate, in order to discuss the intended passage with the pilot. This will include such items as the pilot's planned route, his anticipated speeds and ETAs, both en route and at the destination, what assistance he expects from the shore, such as tugs and VTS information and what contingencies he may have in mind.

The ISM Code was developed in the aftermath of the disaster of the ferry Herald of Free Enterprise (in 1987, with 193 lives lost). It was found that many things had failed, from the bottom to the top of the organization. The task that all shipping companies were to face was to minimize the risk of poor human and organizational decisions that could have negative effects on operational safety, which may eventually lead to accidents. All the organization, from the bottom to the top must be permeated with the safety management culture. The ISM Code addresses the very important issues relating to human factors. Safety is organized by those who are directly affected by the implications of the failure (Kristiansen, 2005, p.481-482). The Code does not describe in detail how the company should undertake the task, butstates that some areas of measures have to be adopted.

The IMO has stated that the objectives of ISM Code are:

- To provide for save practices in ship operation and a safe working environment.
- To establish safeguards against all identified risks.
- To continuously improve the safety management skills of personnel ashore and aboard.
- Preparing for emergencies related both to safety and environmental protection.

The core of ISM (without amendments) comprises 13 Sections over 9 pages in total so it is a short document: the sections are:

1. General
2. Safety and environmental protection policy
3. Company responsibility and authority
4. Designated person(s)
5. Master's responsibility and authority
6. Resources and personnel
7. Development of plans for shipboard operations
8. Emergency preparedeness
9. Reports and analysis of non-conformities, accidents and hazardous occurrences
10. Maintenance of the ship and the equipment
11. Documentation
12. Company verification, review and evaluation
13. Certification, verification and control

The ISM Code may at first glance look relatively complex, but as Bromby (1995) has pointed out, the idea behind the Code is a straightforward learning process which may be illustrated by the next Figure
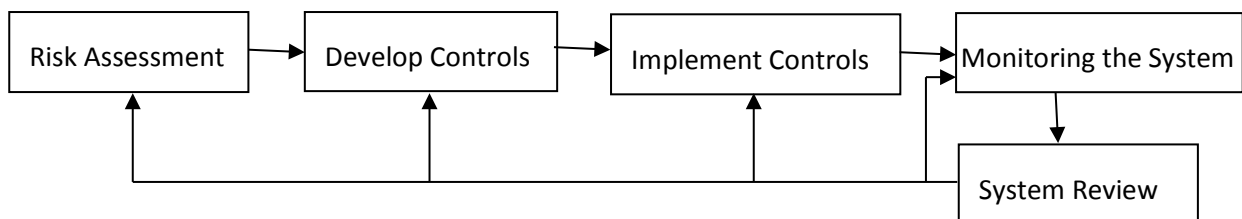


**Figure 33:** The Safety Management Model (from Kristiansen, 2005, p.487). The Risk Assessment can be done by means of Bowtie Models and the controls would be the Barriers.

In order to review the system proactive methods are applied: Inspections, safety tours, surveys and audits. The reactive approach is based on information about accidents, incidents and non-conformities.

# 5.Conclusions

The risk of having an accident at any human activity is never zero. Choices must be made to minimize de risk (Rodrigo de Larrucea, 2015).

From the classical approximation to maritime security, there has always been a reactive safety policy: regulations are enforced to prevent similar accidents to those that have occurred in the past (beginning back from the Plimsoll line at UK in 1876 and the first SOLAS, 1914, to prevent another disaster such as the Titanic). Nowadays, in a quickly changing world with its great exigency standards and agencies (at least at the developed countries) we must be proactive and try to anticipate and prevent any possible accident. The levels of safety at maritime transport must be compared and referenced to the other modes: air, train and road (bus). All these modes of transport have had some accidents in the last years. The transportation by air has cut its casualties from 1 fatality in 2,5 milion departures in 1997 to 1 fatality in 4,5 milion departures in 2015, which is notable (Pavlovičs, 2016[17]).

However, there is a difference in the transportation of passengers by ship. This transport may, in a coarse approximation be divided in two types: short routes by ferry (that must follow a time schedule and a fixed route), or touristic cruising at passenger ships (which spend a week or more travelling circular routes, which may vary with time). The routes done by the passenger ships are usually at relatively calm waters (low latitudes usually) and the route may be changed if there is any inconvenience (a tropical cyclone, e.g.), since passengers are on vacations and presumably having a good time. There is also a great difference that must be considered between air and maritime transport is that usually at the air transport there is no time of reaction, and if the air crashes at land, it is difficult to find survivors. The planes may also land "on water" acting in some way as a sinking ship, with the advantage that they are relatively light since their main construction material is aluminum, not steel. However, these last years the only big passenger plane that has "landed" on water and has been able to save all its passengers and crew has been the Airbus 320 that landed on the Hudson river in NY (USA) whose crew were rightly held as heroes.

From 2005 to the Costa Concordia disaster in 2012, out of more than 100,000,000 people worldwide who have taken cruises, there have been 16 fatalities[18]. This is, one fatality in some 6.25 million departures, comparable to the air transport. However, considering the Costa Concordia disaster on 13

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[17]Pavlovičs, A. (2016): Safety Culture in Maritime domain. Presentation at the 18 International Conference of Maritime Transport (Riga, Latvia). https://failiem.lv/u/er87xbtm?share_email_id=39fac4

[18] http://www.adelaidenow.com.au/news/world/cruising-into-turbulent-waters/story-e6frea8l-1226249831314

January 2012, with the loss of 32 lives, cruising has claimed thus a toll of 48 victims which means a victim each 2,1 million departures in 2012, which is also comparable to the air transport. This has been the last accident with victims at cruise ships (not at passenger ships where the ferry MV Sewol claimed 304 lives in 2014), so the statistic must be improving again.

A difference between the maritime and air transport is that the air transport is dangerous from the moment of take-off to the moment of stopping (as is demonstrated at the tragic flight of Spanair 5022 at Madrid, in 2008, with 154 victims), while naturally, if a ship has an accident entering or leaving a port, the economic inconvenient may be important but with all probability there will be no victims. On the other hand, the death toll of maritime transport may be greater since there may be more passengers aboard. Curiously, more passengers as less regulated are the companies, which has lead to disasters such as that of Doña Paz (1987) and la Joola (2002), not much remembered since they did not take place at occidental countries. MV Doña Paz was a ferry that sank due to a collision at the Philippines, claiming a toll of some 4,386 victims (it is estimated that 2,000 passengers were not listed on the manifest)[19]. The sinking of la Joola, considered to be the second-worst non-military disaster in maritime history, was due to instability and negligence, claimed some 1,863 deaths[20]. In comparison, the worst disaster in commercial aviation has been at the airport of los Rodeos, Tenerife, Spain, in 1977 with 583 victims, when two aircrafts crashed at land (almost 8 times less than the tragedy of MV Doña Paz).

It must be noted (Vlačič, 2016)[21] that cargo has seemed traditionally more important than human transport for maritime legislators (compared to air transport where there was the Warsaw convention in 1929). The transport of passengers and their luggage by sea is regulated by the Athens Convention relating to the Carriage of Passengers and their Luggage by Sea, 1974, with protocols from 1976, 1990 and 2002.

Maritime safety may be analyzed in a holistic way, studying it as a whole. In this perspective, bowtie models may be useful since although they have some limitations, they offer visually a good insight of the problem and if a barrier may be set at each branch (representing a particular source of failure). It is difficult to implement in a bow-tie model the non-linear interaction between different branches and to give a particular probability value to each branch. However, the model may be easily updated.

There are new emerging risks. It must be pointed the gigantism of the new ships (passage ships, containerships of 21.000 TEU, etc), the increase of off-shore platforms. Piracy and terrorism have posed a threat during some time to maritime transport at some areas and still is, but the reaction of the affected countries has been brisk and forceful. However, the threat continues to exist.

The aspects related with protection (*security*) will have in the future more importance and development. Once the vulnerabilities have been identified, the ISPS Code offers an orientation for the preparation, approbation and implementation of the security plans to reduce or eliminate those

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[19]Howard Chua Eo& Nelly Sindayen (1988-01-04). "The Philippines Off Mindoro, a Night to Remember" (https://web.archive.org/web/20071209182552/http://www.time.com/time/magazine/article/0,9171,966394,00.html)
[20]Senegal Marks Anniversary of Ferry Disaster Amid Court Cases. Voice of America. 26 September 2008
[21]Vlačič, P.(2016): Maritime transport of passengers and their luggage in the 21st century. Presentation at the 18 International Conference of Maritime Transport (Riga, Latvia). https://failiem.lv/u/er87xbtm?share_email_id=39fac4

vulnerabilities. ISPS Code must not be considered a single and absolute source (since it is difficult to adapt to every particular country). It must be considered a dynamic instrument that will adapt to the changing nature of navigation, ports, infrastructure and specially, the possible threats.

Construction and design of ships must contemplate in the future the identification of dangers and specific risks for each type of ship (ferries, tankers). The experience about each ship is now easily accessible.

To monitor the state of a ship and thus the maritime security associated, the best instrument is Port State Control (PSC), over other inspections such as Flag State Control (FSG). PSC are more relevant for maritime safety than private inspections (*vetting*).

The consideration towards the seafarers and its wellness is being developed with several laws: Maritime Labor Convention (MLC 2006) enforced in 2013, and the congress at Manila with improvements at SCTW (2010). In Spain there is a new Law of Maritime Navigation that has enhanced the professional criterion of the Master, making it prevail (article 184). It is positive that a collective such as the seafarers that traditionally was uprooted now has a body of laws with rights and also obligations. The seafarer is drifting from the traditional "*romantic*" view of his work and life to an intensive professionalization and modernization.

Analyzing the human factor, probabilistic methodologies are the most common. The human behavior is considered unpredictable. However, continuous formation and health controls of seafarers must ensure that in normal situations, its performance will also be correct. It is in difficult situations when some errors may be made, but modern shipping tries to avoid these situations (*e.g.*, avoiding storms in the route by forecasting).

Relating to event tree analysis and bowtie models, it is difficult to estimate the probabilities of each branch, since there are few occurrences and situation changes with time (the formation of seafarers, technique available, etc…). However, Bowtie models present a graphic insight of the problems that may appear in a situation and clearly establishes the barriers for each, so it may be useful for education purposes. It is true that Bowtie models would not have prevented unexpected accidents such as the one of the Titanic or the Costa Concordia. However, these last years the accidents have a decreasing trend and this is thanks to all the efforts, set by organizations as IMO and EMSA, but also the work of shipping companies, inspectors and the individual effort of seafarers. A good and graphical way to remember an accident is to present it in the form of a tree of events.

Finally, it is normal that richer countries may put more efforts in safety and security while in poorer countries there is no culture of safety (as in our countries some time ago). SOLAS ships have to comply with some standards or they will be detained at some port, but ships that are not SOLAS are precarious at many countries. Let us hope things will be improving step by step. The last trends give some reason for optimism (for example, not a large tanker sunk since 2002), although the guard must not be lowered. As Rodrigo de Larrucea states (translated): "*Safety is an attitude and is never random; it is always the*

*result of a strong will, a sincere effort, an intelligent management and a careful enforcing. Without doubt, it is always the best alternative."* [22]

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[22] Rodrigo de Larrucea (2015): Seguridad Marítima, p. 15. Marge Books.

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*All the articles of Luis Jar Torre(in Spanish, highly recommendable) may be reached at: http://www.grijalvo.com/Batracius/y_presentacion.htm*.

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REVIEW OF LEGISLATION CONSULTED:

COLREG: **International Regulations for Preventing Collisions at Sea 1972.** Last amendment from2007 the text of Annex IV (Distress signals) was rewritten

ICC: **International Convention on Load Lines 1966.** Future amendments (till 2013) have never come into force.

ISM Code: **International Safety Management Code** (adopted 1993). Ensures the safest possible operation of ships and prevention of marine pollution. Mandatory for all passenger ships and all other ships with GT>500 (according to SOLAS, 1994).

ISPS: **International Ship and Port Facility Security** (**ISPS**) **Code.** It is an amendment to SOLAS, from 2002 and enforced in 2014.

PIRACY ACT: Legislation at the UK and Ireland relating to piracy (from years 1670 to 1850)

MARPOL 73/78: **International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978.** Last Annex (VI, prevention of Air Polution) enforced in 2005.

MLC: **Maritime Labour Convention**, 2006 (entered into force 2013)

MoU: **Memorandum of Understanding.** It is not a legal document but an agreement between equals (countries) that organizes inspection of foreign ships (Port State Control). There are several zones.

SOLAS 1974: **International Convention for the Safety of Life at Sea** (with amendments 1988, 2011)

STCW 2010: **Standard of Training, Certification and Watchkeeping for Seafarers**.

Ley de Navegación Marítima, 2014: Spanish law that reforms the existing, encompassing all aspects of navigation (administration, accidents, insurance, chartering, etc…).

UNCLOS: **United Nations Convention on the Law of the Sea.** Base of International Maritime Law. It was concluded in 1982 and came into force in 1994.

# Annex 1. The Bayes' Theorem

The analytic use of trees of events and consequences need the estimation of the probabilities of each branch (a number between 0 and 1, which may be more or less difficult or exact to estimate).

For certain estimations, the Bayes' Theorem may be of some use: the Bayes' Theorem deals with conditioned probabilities, this is, the probability of an event *A given another B* (the occurrence of *B*, is understood). It is denoted *P(A|B)* and may be easily defined mathematically as:

$$P(A|B) = P(A \text{ and } B) / P(B)$$

Two events (*A*,*B*) are statistically independent if an only if *P(A|B) = P(A)*. Then:

$$P(A \text{ and } B)= P(A){\cdot}P(B)$$

The Bayes' Theorem (a mathematical theorem then) thus states that:

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)},$$

It is easily demonstrated.

Many studies have been done, but we will present a simple example of how this could be applied to find a probability that a priori, is not so simple to find:

The probability of a conning officer having an "accident" during his guard or conn, having at least one moment during his guard a Blood Alcohol Concentration (BAC) over 0,05% (as STCW 2010 forbids). If *A* is the probability of having an accident and *B* is the probability of having this BAC, the searched probability is *P(A|B)*. This is not so easy to find since blood samples are never taken aboard. Let us assume the accidents are serious accidents, with total loss, since we have their statistics from the IUMI (Chapter 1).

When there is an accident, however, blood samples are taken and the level of blood some hours ago may be interpolated with the sufficient precision. Thus, we may estimate pretty exactly *P(B|A),* this is, the probability of an officer with BAC> 0,05% having an accident during his conn (at some moment during his conn, it is important for everything to be well-defined). This may be easier to estimate "in theory", but we have observed at the chapter of the Human Factor, with the case of Captain Hazelwood, that there are many discussions about the BAC. We could assume (since we do not have access to BAC records around the world) that this probability is 0,3: this is, that at 3 accidents out of 10, the Officer had BAC>0,05%.

Another probability we may "easily" estimate is *P(A)*, the probability of having an accident with total loss during his conn. If the merchant IMO fleet is approximately 60.000 units (as is stated at Chapter 1), they spend half the time navigating and this means some 60.000x182,5 days x 6 conns/day=67,5 million conns and the number of "accidents with total loss" has been of some 50 (decreasing these last years). As it may be seen, we do not need to be exact since the uncertainty at others factors may be greater. And we may hope that all the uncertainties will "smooth up" or compensate altogether. The probability *P(A)* is then $50/6,75 \cdot 10^7 = 7,4 \cdot 10^{-7}$ or less than one in a million (not big).

More difficult is to estimate *P(B)*. Some officers never drink in duty, these are the best. Others may usually drink a little, maybe to relax just after the conn, hoping that the alcohol level will decrease quickly. Others may drink heavily at some special occasion (their birthday, if they receive bad news, etc…). The probability does not differentiate if they were absolutely drunk or only a little (other more complex may), and even it does not differentiate if the accident was the officer's fault (it could be not, but statistics are cold, and evidently someone will always get more chances of getting blamed if he was drunk).

According to Egozcue*et al* (1997)[23], one way to calculate this probability could be carrying an informal interview with several experts in the problem and taking directly the mean of the gathered values (which may be only four or so). However his methodology or suggestion has not been widely adopted (analyzing big data trends nowadays seems to be the last tendency). In this case we are going to guess a value directly: *P(B)*=1/300 (in one out of 300 conns, which means once in mean every 37 working days, an officer is "drunk" at the bridge).

With the three estimated values we may then estimate the last probability, the one that was more difficult to estimate *a priori*.

$$P(A|B)= (0,3) \cdot (7,4 \cdot 10^{-7}) / (1/300)=6,67 \cdot 10^{-5}$$

This is, a drunken officer will have "in mean" almost 7 accidents (6,67) in 100.000 conns. Being "drunk" increases thus the probability of having an accident with total some 100 times (90 exactly=$5,3 \cdot 10^5/6 \cdot 10^{-7}$: they are not independent events thus). Another great advantage of Bayes' formula is that we may study the sensibility of the result changing certain values.

For example, let us consider that as it is seems with the latest trend, accidents with total loss are decreasing (for example, because new ships are better designed). Let us suppose it has decreased from 50 to 40 a year (it must be remembered that in 2014 the number of accidents was 27). Then *P(A)*=$40/6,75 \cdot 10^7 = 5,9 \cdot 10^{-7}$ and *P(A|B)*=$5,33 \cdot 10^{-5}$. The probability of having an accident are thus reduced in the factor (40/50), but the probability of having an accident conditioned to having BAC>0,05 has the same increase: 90 times (which seems reasonable).

It is true that these probabilities change with time so it is difficult to define absolute values. Each generation of seamen is different, have different formation, priorities. Evidently, the discipline imposed

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[23]Egozcue, J. J.; Simarro, G.; Díez, P. Vulnerabilidad sísmica y toma de decisiones. "Revista internacional de ingeniería de estructuras", May 1997, vol. 2, n. 1, p. 35-58. http://hdl.handle.net/2117/8283 (in Spanish).

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by the companies and STCW hinder the consumption of alcohol, especially among the officers that may not have a hard physical work nowadays but carry a lot of responsibility.

# Annex 2. Simple Derivation of the Long Wave Equation.

We consider it interesting to present this original derivation that is a comprehensible model. There are many other formulations but they are much more cumbersome. The results obtained are coherent with linear theory of water waves, evidently (e.g. Dean and Dalrymple, 1991).

The necessary premises are minimal:

F=ma    m=mass (*kg*)    a=acceleration (*m/s²*)        Incompressible fluid

P=ρgz   (z=distance to the water surface)=pressure=F/A (Force/Area)

ρ = density of water≈1000 *kg/m³*                g=Acceleration of gravity=9,81*m/s²*
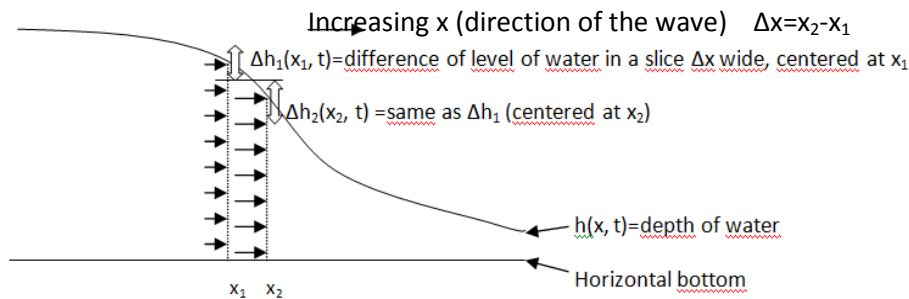


**Figure A2.1:** *Lateral view (or cut) of a water wave (advancing towards the right)*

Assumptions:

Mild slope of the water surface, surface slowly varying ($\partial h/\partial t \approx 0$; $\partial h/\partial t \approx 0$)

The increment of **pressure** is constant at the whole column of water (long wave hypothesis)

Then, the acceleration (eulerian, at a fixed point) of the water particles of the control surface 1 will be: (a=PA/m)

$a_1 = h\rho g \Delta h_1 / \rho h \Delta x$  (acceleration directed to the right in this case)

And of course, for the control surface 2 will be:

$a_2 = h\rho g \Delta h_1 / \rho h \Delta x = g(\partial h/\partial x)_2$

On the other side, by continuity of the volume of an incompressible fluid we have:

$(\partial h/\partial t)\Delta x = (v_1 - v_2)h$

Being v the horizontal velocity at the surfaces 1 and 2. At the end there is a more detailed demonstration in 2D.

But the velocity is the integral over time of the acceleration:

$$\frac{\partial h}{\partial t}\Delta x = \left[\int_0^t (a_1 - a_2)dt\right] h = gh\left[\int_0^t \left\{\left(\frac{\partial h}{\partial x}\right)_1 - \left(\frac{\partial h}{\partial x}\right)_2\right\} dt\right]$$

g is constant. Now, it is almost done: since Δx is also a constant, it can go inside the integral, and making Δx tend to 0 we have:

$$\frac{\partial h}{\partial t} = gh\left[\int_0^t \frac{\partial^2 h}{\partial x^2} dt\right]$$

Now we also assume that at t=0 the water is calm. Then we derive both sides with respect to t.

$$\frac{\partial^2 h}{\partial t^2} = gh\frac{\partial^2 h}{\partial x^2}$$

We have made the assumption that $\frac{\partial h}{\partial t}$ is little (≈0).

The previous equation is the wave equation, very well known in physics (vibration of strings, drums, electromagnetic waves, etc…). However, we must do a last and important assumption, and is that the variation of the water depth is negligible compared to the depth.

We can then make h=d+η, where:

d=depth of water at the mean water level (MWL)

η=variation due to the wave, and we assume η<<d

The equation is then:

$$\frac{\partial^2 \eta}{\partial t^2} = gd\frac{\partial^2 h}{\partial x^2}$$

Assuming a bottom of constant slope, $(\partial^2 d/\partial x^2)=0$. If we do not accept this approximation a source function for the equation will appear. The equation is complicate to solve otherwise since the free surface is an unknown.

$$\frac{\partial^2 \eta}{\partial t^2} = gd\frac{\partial^2 \eta}{\partial x^2}$$

And now this is the well known wave equation. In 1 dimension its solution is:

$$\eta(x,t) = F(x\text{-}ct) + G(x\text{+}ct) \qquad \text{where } c=\sqrt{gd}$$

The solution is then any wave travelling to the right with constant shape superposed to another wave travelling to the left, always at speed c.

If the wave is periodic, the velocity or speed relates the period T and the wavelength L (c=L/T).

The pressure pulse in this case travels exactly with the wave, since it causes ΔP that drives the movement (other forces may be Coriolis force, etc…).

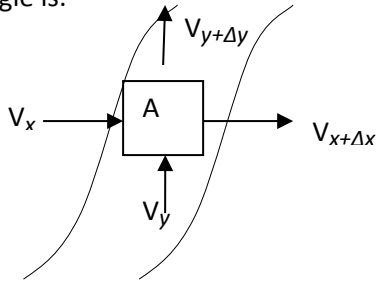To extend this equation to 2D we must assume a square view in plan. The area of this square, or rectangle is:



**Figure A2.1:** Plan view (from above) of a column of water with a long wave passing.

The column of water is *dx* wide in the horizontal direction and *dy* in the vertical. Thus:

*A=dx·dy* is its area, and its volume, evidently:

Vol=A·h(x,y,t)=*dx·dy*·h(x,y,t)

The increment of the volume per unit time that enters this area is:

dVol/dt= $(v_{y+\Delta y} - v_y)$h*dx*+ $(v_{x+\Delta x} - v_x)$h*dy*

Operating a little the 2 previous equations, and taking the limit, we have:

$\partial h/\partial t = h\ (\partial v_y/\partial y + \partial v_x/\partial x)$, which is the well known equation of continuity in 2D. With the same reasoning as before (1D case) we have:

$\partial^2 h/\partial t^2 = gh\ (\partial^2 h/\partial y^2 + \partial^2 h/\partial x^2) = gh\boldsymbol{\Delta}h$

Where $\boldsymbol{\Delta}$ is the Laplacian operator (do not confuse with increment Δ). Making the same assumptions as before we have:

$\partial^2 \eta/\partial t^2 = gd\cdot\boldsymbol{\Delta}\eta$

Which is the wave equation that may be generalized to n dimensions.