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PROBABILISTIC MODELING OF SHIP GROUNDING
A review of the literature

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Abstract

This is a literature review about exiting geometrical models for analyzing the risk of ship grounding. Geometrical model presents the geometrical probability of ship grounding. Almost all the major existing models (12 models in total) were reviewed and analyzed. The advantages and disadvantages of each model have been presented and some comparisons between them have been performed.

Ship grounding accident is one of the major accidents in shipping industry. The probability of this phenomenon is usually calculated by multiplying two probabilities named geometrical and causation probabilities. Geometrical probability gives the probability of a ship being a grounding candidate, which means those ships that will run aground if they do not do any evasive actions. Consequently, the causation probability will give the probability of a grounding candidate not to do any evasive action and then goes aground.

There are many factors that affect the causation probabilities; factors like season, dimension of the ship, time of the day, etc. The causation probabilities can be estimated and calculated by statistical analyzing of the previous accidents and the involved factors. The geometrical probability, however, will be yielded by modeling the ships’ traffic and navigation in the specific waterway.

The report is the first stage of analyzing the risk of grounding in the Gulf of Finland. The focus of this report is mostly on existing and used geometrical models for analyzing the risk of grounding in different parts of the world. Besides the most used values for causation probabilities for calculating the risk of grounding have been collected and presented. Some recommendations for improving the models have been suggested as well..

Keywords (and classification)

Ship Grounding, Ship Stranding, Risk Analysis, Causation Probability, Geometrical Risk Modeling

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Preface

This report has been written within SAFGOF-project, which is a multidisciplinary project conducted in Kotka Maritime Research Center by Universities of Helsinki and Turku, Helsinki University of Technology and Kymenlaakso University of Applied sciences. In the SAFGOF-project, the accident risks of marine traffic in the Gulf of Finland are estimated in the current traffic situation and in the year 2015. Also, the direct environmental effects and the risk of environmental accidents can be evaluated. Finally, the effects of national and international legislation and other management actions are modeled, to produce advice and support to governmental decision makers. The aim of this study, conducted by Helsinki University of Technology, Department of Applied Mechanics, is to report the state-of-the-art in probabilistic modeling of ship grounding within marine traffic risk assessment.

For funding the project, the author wishes to thank European Union, European Regional Development Fund, Regional Council of Kymenlaakso, City of Kotka, Kotka-Hamina Regional Development Company Cursor Ltd., Kotka Maritime Research Association Merikotka, and Kotka Maritime Research Center Corporate Group.

The author is also grateful to D.Sc. Jakub Montewka, M.Sc. Floris Goerlandt, Prof. Pentti Kujala and M.Sc. Maria Häninnen for their advices and comments on this report.

In Espoo, 5 June 2009

Arsham Mazaheri

List of Abbreviations

AIS	Automatic Identification System
BN	Bayesian Network
DWT	Dead Weight Tonnage
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Navigational Charts
FTA	Fault Tree Analysis
GOF	Gulf of Finland
GPS	Global Positioning System
GRT	Gross Register Tonnage
GT	Gross Tonnage
PDF	Probability Density Function
PRA	Probabilistic Risk Analysis
SGRA	Ship Grounding Risk Analysis
VLCC	Very Large Crude Carrier
VTS	Vessel Traffic Service

1. Introduction

“Man was limited more by his visions than by his tools” (Christopher Columbus)

Since the ship grounding risk analysis (SGRA) is not a new subject in shipping industry, the amount of related literature is not few. However, most of these researches have been done in a general perspective[1-3] or by focusing in Tanker grounding phenomenon[1][4-6]. Some of the mentioned reports have tried to express general views about SGRA[1, 4]. However, it should be borne in mind that since the affecting factors in SGRA highly depend on the traffic and weather conditions of the region, in where the research was conducted, they cannot be generalized for all regions. In addition, SGRA is not a one-time research, and since the traffic and weather situations are changing during the time, SGRA should be a dynamic process to be able to cope with the new risks coming.

Ship grounding phenomenon accounts for about one-third of commercial ship accidents [1, 7]. For instance, about 20% of all tanker losses between 1987 and 1991were due to grounding[4]. Zhu et al.[2] (cited in [8]) have reported that the total losses of all ships during the period 1995-1998 were 674 in numbers and 3.26 M in Gross Tonnage (GT), where 17% in number and 24% in GT were due to grounding. Also more than half of all the accidents in the Gulf of Finland (GOF) are grounding accidents [9], where 48% of them occurred near islands or in narrow waters[3] (cited in [8]). Moreover, 47% of all accidents of the Greek ships larger than 100 GT all over the world between years 1992-2005 were reported as grounding [8].

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[1] The researches related to structural damages or structural risks were excluded from this review.

[2] Zhu L., James P., Zhang S., 2002, Statistics and damage assessment of ship grounding, Marine Structure, 15:115-530

[3] Kujala P., Luukkonen J., 1999, Ship grounding in Finnish waters, Maritime Institute of Finland, Maritime Res News. 14:3-5

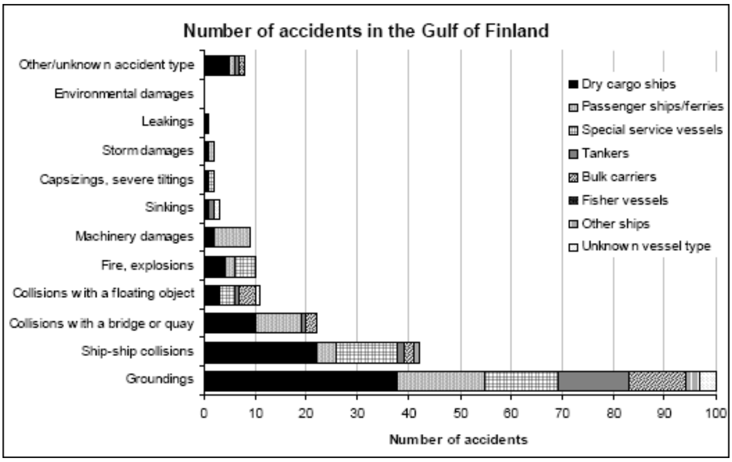

Figure 1: Number of marine accidents happened in the Gulf of Finland between years 1997-2006 (Source [9])

As can be seen in Figure 1, ship grounding is the major accident in maritime transportation[1]; while the total amount of researches that have been done about SGRA is quite few in comparison with the researches about ship collision. Most of the surveys about ship grounding have analyzed ship grounding in mechanical point of view.

The risk of ship grounding can be divided into two major parts: 1- Physical risk and 2- Economical risk [1]. The physical risk concerns about the occurrence risk of an accident like the probability of grounding or collision under specific conditions; while the economical risk talks about the risk of economical loss due to an occurred accident like the cost of oil spill clean-up or the environmental effect of an oil spill [1]. The focus of this research is on physical risk, and the economical risk is not in attention. However it might be considered somehow occasionally.

1.1 Risk

In the Probabilistic Risk Analysis (PRA) the risk is defined as a product of the probability of an unwanted event and the magnitude of its consequences. Mostly, the consequences can be presented as lost, and it can be calculated by money, human lives, environmental issues, time, etc.

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[1] Grounding is the major maritime accident in the Gulf of Finland, while it has the second rank, after collision, in global perspective.

$$Risk = Probability\ of\ Occurrence \times Consequences \qquad \textbf{(1.5.1.1)}$$

In this study, the main concern is the probability of occurrence of an unwanted event; and the consequences are not in the interest. Therefore, wherever the word "*Risk Model*" is mentioned, it is meant the model for the occurrence probability of the unwanted event (in this case ship grounding) and the consequences of the event are not considered.

1.2 Probabilistic risk assessment of ship grounding

Nowadays most of the risk assessments on ship grounding are done by the help of Macduff's [3] and Fujii's [2] first ideas. They have used the notion so-called Grounding Candidates to calculate the numbers or the probability of grounding accident by different given conditions known as Causation Probabilities.

Grounding candidates are those ships that would most probably go aground if nothing, internally or externally, changes; it means that if nobody onboard does any evasive actions or the environmental situation does not change[1]. It can be presented as:

- The number of the ships in a given time unit that are grounding candidate

$$Number\ of\ Grounding = Grounding\ Candidates\ Number \times Causation\ Probability \qquad \textbf{(1.5.1.1)}$$

- The probability that a ship is a grounding candidate.

$$Probability\ of\ Grounding = Grounding\ Candidates\ Probability \times Causation\ Probability \qquad \textbf{(1.5.1.2)}$$

The causation probability informs how probable would be that the situations do not change in favor of the ship, in different given scenarios. The factors affecting on causation probability are discussed in Chapter 2.

---

[1] Some say that "if the ship navigates blindly".

1.3 Grounding and its different types

Ship grounding in general is a type of marine accident that involves the impact of a ship on the seabed or waterway side. It results damage of the submerged part of her hull and in particularly the bottom structure, potentially leading to water ingress and compromise of the ship's structural integrity and stability. Grounding applies extreme loads onto ship structures and is a marine accident of great importance due to its impacts. In less grave accidents, it might result to just some damages to the hull; however in most serious accidents it might lead to oil spills, human casualties and total loss of the vessel.

Ship grounding can be categorized into two major groups:

- Powered Grounding
- Drift Grounding.

Powered grounding has the largest portion of total groundings [5]. It happens when the ship is moving forward (or backward) on her power, mostly because of navigational errors [10]. Different authors like [4] have mentioned that fundamental failures in the process of passage planning and piloting are the most reason for powered grounding.

Figure 2: The *Empress of the North* struck Rocky Island while navigating a 90 degree turn to starboard about 50 nautical miles (90 km) from Juneau, Alaska in Icy Strait on May 14, 2007, [Type 1, refer to Figure 6](Source: http://www.nowpublic.com/us_coast_guard_photo_of_grounding_of_alaska_cruise_ship)

The error in nautical charts or late update of these charts is the other main reason for powered grounding. Since using the most advance techniques for sounding is quite expensive procedure [4], most of the available charts have used old data or inaccurate sounding devices and procedures to prepare the electronic nautical charts. Amrozowicz [4] has mentioned that about 60% of the soundings shown on nautical charts for U.S. waters are based on lead-line surveys conducted over 45 years ago. In addition, some ships are not using electronic charts, and conventional paper charts are still in use. The other issue is that not all the coastal areas in the world have been covered by the Electronic Navigational Charts (ENC). However, for the Gulf of Finland, 100% of the coastal areas have been covered by ENC [11] and those ENCs are commercially available. Therefore the question is how accurate are these ENCs and how many of the presented ships in this area are carrying an Electronic Chart Display and Information System (ECDIS), which is an essential device to use ENCs.

Figure 3: An Ocean Discovery Catamaran ran aground in West Maui waters, Honolulu**,** on May 18, 2007, [Type 2, refer to Figure 6] (Source: http://archives.starbulletin.com/2007/05/19/news/briefs.html)

In comparison, drift grounding happens when the ship is drifted to coast or a shoal by current, wave or wind. It mostly happens after a mechanical failure [10], such as lost of power or steering failure. Unfavorable weather conditions, failed anchoring and failed tug assistance might contribute to drift grounding as well.

Figure 4: Liberian bulk-carrier cargo ship, M/V Fedra, ran aground and smashed against the southernmost tip of Gibraltar on October 10, 2008 by the wind blowing about 125 km/hr [Type 3, refer to Figure 6] (Source: Unknown)

Figure 5: The storms forced the Dutch cargo ship, *Artemis*, to run aground in Les Sables d'Olonne, on the French west coast, March 10, 2008. The ship had been driven onto the coast by the wind blowing more than 130 km/hr. [Type 4, refer to Figure 6] (Source: Reuters/Stephane Mahe)

The grounding phenomenon can also be divided into two other different groups [12] (Figure 6).

- Soft Grounding
- Hard Grounding

Soft grounding is when the ship runs aground on sandy beaches (Figure 3 & Figure 5) and consequently hard grounding is when the ship grounds on rocks or is smashed to the rocky side of the coasts by wind or waves (Figure 2 & Figure 4).

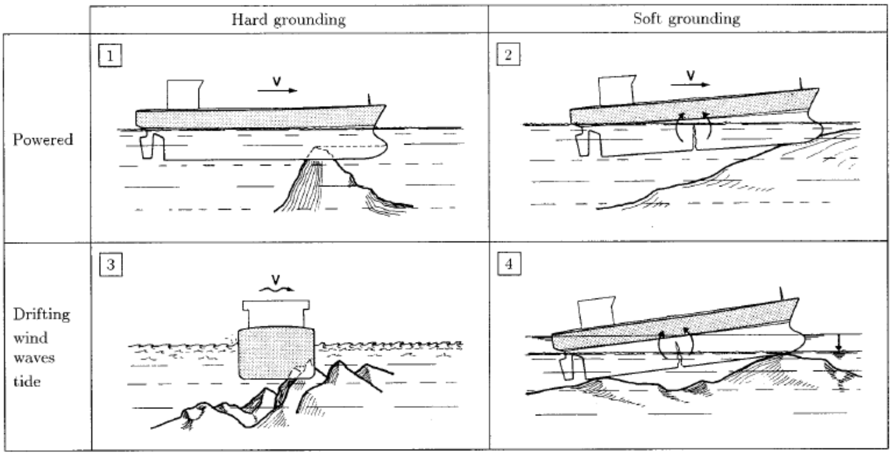

Figure 6: Four main categories of grounding (Source [12])

1.4 Grounding or Stranding?

During the literature review, the author has found that the two words, *Grounding* and *Stranding*, have been used to express the phenomenon of a ship being stock in shallow waters or on shore, or impacting the ground of the sea. It seems that there is no unique idea about the specific word that should be used for this phenomenon. Except Kristiansen [13], the others have not considered any differences between these two terms. All the others, except Fujii [2], have used the word grounding to call this specific phenomenon. Fujii, however, preferred to use the term stranding and defined it as every kind of grounding except intentional grounding. Kristiansen [13] has separated them from each other and has mentioned that *"the term **stranding** is used for the impact with the shore line in contrast to the impact with individual shoals and islands in the fairway* [**Grounding**]"

It also seems that this disparity cannot be addressed by checking some well-known ordinary English dictionaries like Merriam Webster or Longman.

Merriam Webster online dictionary [14] has mentioned that *stranding* actually is the same as *grounding* (Strand: to run, drive, or cause to drift onto a strand:

run aground). It could also be understood that a situation could be called stranding when the ship has been situated in an unfavorable condition; like when she loses her power and remains helpless at the mercy of waves, wind or current (Strand: to leave in a strange or an unfavorable place especially without funds or means to depart).

On the other hand, Longman has mentioned that if a boat or ship hits the bottom of the sea so that it cannot move, it is said that it has been grounded.

On balance, it can be said that the differences between these two words cannot be revealed so easily and at least it needs a deep linguistic research on the roots of the words. However, the author of this report has found beneficial to assign each of these two words to a specific phenomenon. Therefore, in this report, the definition for each of these words would be quite similar to the definitions that Kristiansen [13] has mentioned in his book. It means:

- **Stranding** is the event that a ship impacts the shore line and strands on the beach or coast. It happens when the track of a ship intersects the shoreline by either navigational error or drifting.
- **Grounding** is the event that the bottom of a ship hits the seabed. It happens when a ship is navigated through an individual shoal in a fairway while her draught exceeds the depth.

The only remained problem is when the ship impacts with an island through her path in a fairway. Since in this case the ship might be stranded on the coast of the island, the event can be called stranding. On the other hand, since the island is located in the middle of a fairway, it can be considered as a shoal and therefore the phenomenon can be called grounding. Nevertheless, in this report, this specific case also will be called grounding (same as Kristiansen) for the sake of easiness to refer in geometrical modeling.

It should be borne in mind that in this report the word grounding has been used in general for both grounding and stranding events except wherever they have been clearly referred by their defined names (grounding/stranding).

Now, after all, the question is that if all of these definitions are required or not. In the other words “Does the exact definition for the event (grounding or stranding) change the way that the event should be analyzed?” Kristiansen [13] believes that it does. However, other researchers have not separated them clearly.

1.5 Report's scope, limitations and outline

1.5.1 Scope

The aim of this study is to find and analyze the different existing models in the area of grounding risk modeling. This study will be the base for the next stage of the research, which is adopting or modifying a suitable model for the grounding risk analysis in the Gulf of Finland. This research has been conducted in Helsinki University of Technology, Maritime Institute of Finland.

1.5.2 Limitations

The models presented in this report have been collected from the most cited articles and books in the literature of related area. The main focus of this report is geometrical models and it is probable that some mathematical models exist that the author has not mentioned in this report. This report focuses on physical risks of grounding and the economical risk is not in attention.

In different parts some discussions have been done by the author. They are the author's own opinions about the subject, and should not be accepted without being examined.

1.5.3 Outline

The report consists of 7 chapters in following order:

- Chapter 1 describes the aim of the study and defines the scope and limitations of the study. A brief view and short statistics about the grounding phenomenon and the used terms are presented.

- Chapter 2 presents different factors affecting the grounding event, and ideas about the causation probability and the factors that might have effects on it

- Chapter 3 provides a list of existing models sorted chronologically. It also contains the author's analytical views on the models and some comparisons between different models

- Chapter 4 concludes the study and also includes some of the author's opinions and questions regarding to the subject

- Chapter 5 presents some ideas and suggestions for further researches

- Chapter 6 presents the complete list of the references used in this study

- Chapter 7 contains the appendix of this report, which is a complete list of collected causation probabilities

2. Different Affecting Factors on Risk of Grounding

“Anything that can go wrong will go wrong” (Murphy’s Law)

As has been mentioned in Chapter 0, the probability of grounding is calculated as the product of the probability of being a grounding candidate and the causation probability. There are different internal and external factors that affect on both probabilities. Internal factors are those that are related to the ship, herself; and external factors are those that will appear depend on who navigate the ship and also on the environmental situations related to the location of the ship.

Different authors [1, 5, 15-19] have mentioned different factors. The affecting factors can be divided into five major categories:

1. Human factors
2. Vessel specifications
3. Route characteristics
4. Atmospheric factors or weather conditions
5. Situational factors

These all have been explained in more detail below.

2.1 Human Factors

Human factors are all those factors related to human and his interactions with the vessel. Human factors can cause human errors [20] and human errors may end up with an accident like grounding. As Hänninen [20] mentioned in her report, recently group and organizational factors’ contributions in human errors together with individual factors are being considered as human factors for risk analyzing in safety issues.

Human and organizational factors had between 60%-80% contribution in maritime accidents and causalities [1, 21]. Therefore, it can be concluded that human factor is the most important risk factor in the maritime safety. On the other hand, it is the hardest one to model. Jebsen et.al. [1] has replaced the human factors by the effect of vessel’s flag. He assumed that the vessel’s flag can be used as a proxy to estimate the level of crews’ skills. This procedure (using proxies) could be useful whenever the affecting factors are hard to be analyzed precisely. Although this assumption might help to simplify the analysis, it can lead to over- or underestimate the effects of a factor.

The collected human factors[1] can be divided into three main categories:

1. Mind concern issues
2. Composition, competence and attitude of the ship's crew
3. Company and organizational factors

- ***Mind concern issues*:**
    - Excessive fatigue; It might be caused by overtime working, inability to sleep during time-off due to severe motions of the vessel, or even by stress
    - Excessive usage of alcohol; Goodstein [6] has mention the term of "Saturday Effect" in his paper, which is illustrating that tanker oil spills happen more frequently in Saturdays. Although he couldn't find an exact explanatory reason, it might be considered as an interesting effect of alcohol usage.
    - Excessive stress, which can affect on crews' performance by disturbing their concentration or causing fatigue. Amrozowicz [22] has cited in his thesis, from [23], that a certain level of stress will maximize the level of individual performance, while the stress above that specific level will dramatically decrease the performance (Figure 7).

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[1] Human Factor is a broad area and most probably covers more issues than what have been mentioned here.

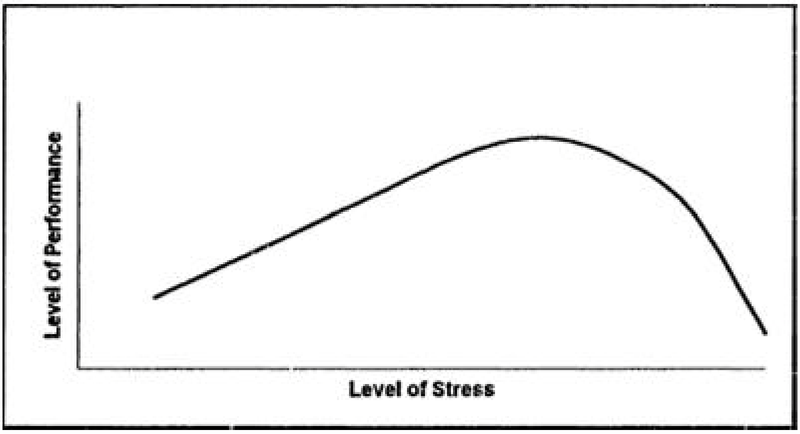

Figure 7: Effects of stresses on Performance (Source [23] cited in [22])

- Just Woke Up; which means that the duty starts right after waking up. For instance, the master is waken up to make a decision in a critical situation

- ***Composition, competence and attitude of the ship's crew***

  - Experience of nautical officers, that could be increased by being in a same situation or location before or by the years of being in the duty
  - Skills Level, that can be affected by the quality, level and the duration of training and duty
  - Occupation with other jobs, like writing the log book or sketching the followed path, which would make the watch-keeper to not having full concentration for his duty
  - Blind acceptance;

    - Following the pilot decisions blindly without any comments; It has been recommended that the master or the bridge officer think about the pilot’s decision and inform him if his orders are not match with the previous plan of the route
    - Blindly trust the information that comes from the navigational devices; crews have been recommended to think about these kinds of information and check them if they seem abnormal.

  - Not following the order due to personal decision; although this is a really rare situation in hierarchy management system of a ship, it should not be neglected. It may occur when the crew has too much self-confidence.
  - Language Problems; It happens when the crews are mixed from different nationalities with no common mother tongue. It also can be categorized under the company and organizational factors.
    - Communication difficulties between Pilot and Master or other crews, specially between Pilot and Helmsman or bridge officer, due to different languages

- ***Company and Organizational Factors;***

  - Company bureaucracy or regulations; for instance the decision makers pyramid in the company or punishment and blame cultures existence in the company may affect the way that the crews will or can perform their duties
  - Crew size and standard required manning; the size of the crew should always meet the standard required manning for the vessel, otherwise it might resulted to overtime working or occupation with other jobs for crews

2.2 Vessel Specifications

Vessel specifications are those factors that are directly connected to the vessel, like her dimensions and her abilities. They can be listed as below:

- Length, breadth, and draught
- Size
  - Fujii [2] has mentioned that the grounding risk may not be related to the size of the vessel (Gross Tonnage), while it is definitely related to ship's draught. Since the ships' draught, at the time of the accidents, have not been mentioned in most of the accidents reports [1], the SGRA could be done by considering the length of the ship as a proxy for draught [2].
  - In contrary, Samuelides et al. [8] have found that larger ships (>30000 GT) are less involved in grounding rather than smaller ones (>500 GT). He has concluded that the type of the accident and the size of the vessel are not statistically independent.

- Wind exposure area of the ship; it has effect on wind drift force affecting on the ship
- Trim, list and heel angles
- Type of the ship
    - Samuelides et al. [8] have extracted from the Greek accident database that the dry cargo vessels suffer the most from grounding.

- Maneuverability; Yavin [24] believes that the maneuverability of a ship is related to her draught and also the depth of the waterway.
- Nationality or the flag state; as Jebsen et.al. [1] has did, it can be used as a proxy for human factor or it can be considered as a proxy for safety culture of the flag state
- Age of the vessel
    - Samuelides et al. [8] have argued that statistics shows the older ships are more involved in grounding rather than younger ships. They have related it to the advanced navigational equipment on board and more reliable mechanical parts of the younger vessels. However, they have concluded that since the ratio of grounding over the total number of accidents does not depend on the ship's age, the type of the accident and the age of the ship are statistically independent.

- Onboard navigational aids, like GPS, ECDIS, etc.
- Nautical Charts; availability and quality
- Bridge design; for instance in older ships the steering, radar and charts were located separately in different places of the bridge, which made the bridge officer to leave his position in order to check the position or make any changes in the charts. Nowadays mostly they are located in one place, which makes the bridge officer to steer the ship while he has full control on charts and radar etc.

2.3 Route Characteristics

Route characteristics are the factors connected to the fairway, like its dimensions, and presence and type of navigational aids along the waterway. They can be listed as below:

- Length, depth and width of the waterway
- Depth uncertainty, it can be mentioned in the Nautical Charts

- Number of changing courses and their level of difficulties
- Traffic volume or density[1]
- Location of the vessel; if the vessel is navigating in Open sea, Offshore area, Coastal area, Inner coastal area or Port area [25][2]
- Composition and consistency of the sea bed
- Slope of the sea floor
- VTS (Vessel Traffic Service) zone

2.4 Atmospheric Factors or Weather Conditions;

The following factors are included in this category:

- Wind; speed and direction
- Current; speed and direction
- Wave; height and direction
- Swell
- Tide
- Visibility
  - There are different ideas about good visibility and its defined range. Kite-Powell et.al. [7] has defined good visibility as if above 2 km range is visible, while Fowler and Sørgård [10] set it as 4 km. It presents the need for kind of global agreement to define each variable (affecting factor) internationally; otherwise the calculated risk would differ from place to place and it leads to unclearness about risk concept.

- Ice condition (in arctic regions)
- Time of the day

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[1] These terms have been discussed more in part 3.1.2

2 In coastal areas, evasive movements can be made without any noteworthy obstacles or a risk of grounding. Inner coastal area means archipelago or a narrow waterway area, in where evasive movements cannot be made freely without a risk of grounding. The order of the areas, from open sea to the port, is Open sea-> Offshore -> Coastal -> Inner coastal -> Port. {Correspondence between the author and Ms. Maria Hänninen from Merikotka Research Center (Translated from [25])}.

One other definition that is being used in New Zealand is: Unlimited -> Offshore -> Coastal -> Inshore -> Enclosed. Offshore is defined as 100-300 nm off the coast, coastal is around 20-30 nm (based on the economic zone), inshore is to the 12 nm territorial limit, and enclosed is basically ports, bays and rivers. [Correspondence between the author and Mr. Dingo Tweedie from SGS (NZ) Ltd.]

    - Fujii [2] has mentioned that the risk of maritime accidents would be increased during the night time and darkness.

- Availability of weather forecast
- Differences between forecasted and seen weather conditions. (How reliable the forecast would be in that specific region.)

2.5 Situational Factors

Situational factors are those factors that will be presented according to different situations and cannot be categorized in above categories, like presence or absence of pilot on the bridge. Some may argue that this category can be split up into above categories. However, the author believes that having this category will help us later to have a clear view about different affecting factors and then lead us to find more accurate geometrical model or causation probabilities.

- Availability and quality of pilot's assistance
- Availability and quality of tug assistant
- Loading conditions; for instance Fowler and Sørgård [10] believe that being in ballast condition will make the drift speed higher than normal.

2.6 Affecting Factors and Causation Probabilities

The factors explained above have effects on both the probability of being a grounding candidate and on causation probabilities. Most of these affecting factors have been analyzed in reviewed literature. Most of the common expectations have been verified, like the effect of poor visibility or high wind speed in associated risk of grounding. However, the issue that has not been considered precisely is the level of contribution of affecting factors in the associated risks. For instance, the common belief about poor visibility is that poor visibility involves higher grounding risk. Nevertheless, it would be more accurate if the exact increase in grounding risk for each kilometer decrease in visibility could be found. The same procedure is recommended for the other factors.

The mentioned affecting factors are related to each other or can affect each other. For instance, the loading conditions affect draught, list and trim angles; or speed and maneuverability of the ship can affect heel angle; or the maneuverability of the ship can be related to its dimensions and its size. This fact should be considered while their probabilities are being calculated; for instance with the help of Bayesian Network (BN) or Fault Tree Analysis (FTA). The author's general belief is that when the negative effects from some factors like time of the day (darkness) increase, it can somehow be compensated with some other factors like increase in bridge crew awareness. Although this theory has been mentioned more or less by Macduff [3] and Fowler and Sørgård [10], it still needs to be examined.

Some authors have calculated a general causation probability for grounding risk analysis[1]. Although most of them have calculated the causation probability for different scenarios and locations separately, but at the end most of them recommended a general causation probability.

Nevertheless, since the causation probability for ship grounding will not be the same for all scenarios and seasons (due to different traffic density, weather conditions, daylight duration, etc.) a general causation probability cannot reflect the actual risk of grounding. Therefore, it is recommended to define the causation probabilities for each scenario separately or at least define them regionally. Hänninen [26] has mentioned that different ways to estimate causation probabilities are:

1. Use accident statistics
2. Adjusting previous values for causation probabilities to the local conditions
3. Fault Tree Analysis (FTA)
4. Bayesian Network (BN)
5. Expert judgment

She also has mentioned that when the probability of being a grounding candidate is modeled based on AIS-data (Automatic Identification System), it automatically includes local features.

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[1] The complete list of collected causation probabilities is available in the Appendix.

3. Existing Risk Models

"It is most likely that something unlikely will happen" the question is "how to plan when you cannot predict!" (Aristotle)

The collected models are divided into two groups as:

- **Analytical Models,** which are those that the ships' traffic distribution have not been used for defining the model.
- **Statistical Models,** which are those that the ships' traffic distribution have been taken into account while the models have been designed.

Each group has been sorted chronologically.

3.1 Analytical Models

The models that are considered in this part are:

- Macduff, 1974
- Fujii, 1974
- Kite-Powell et al., 1999
- Fowler and Sørgård, 2000
- Kristiansen, 2005

3.1.1 Macduff, 1974

Macduff [3] has defined his work as an attempt to find the probability of grounding. However, according to the definition of this report, his work actually shows the probability of stranding.

Macduff argued that the real probability of grounding (P_{RG}) would be the product of Geometrical Probability (P_G) and Causation probability (P_C).

$$P_{RG} = P_G \times P_C \tag{3.1.1.1}$$

where:

P_G is the probability of being a grounding candidate or being in a course of grounding.Grounding candidate means those ships, which will run aground if they do not do any evasive action

P_C is the probability of failing to do an evasive action in order to avoid grounding

Then he has mentioned that the geometrical probability of random grounding (assuming random navigation through the channel) can be calculated as[1]:

$$P_G = \frac{4T}{\pi C} \tag{3.1.1.2}$$

where:

T is the track length of the ship or stopping distance. T is also a function of the size and speed of the ship, which is estimated to be equal to 20 times of the length of the ship [3].

C is the width of the channel or waterway

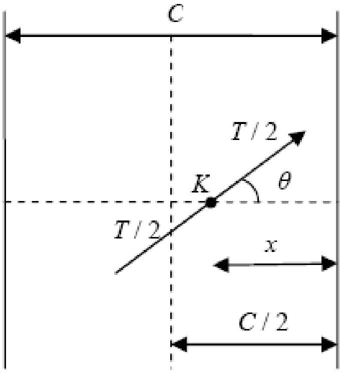

Figure 8: Probability of hitting the wall of the channel according to Macduff [3] (Source [27])

First perspective

Macduff has used Buffon's needle problem, which is a 2-Dimensional model, to find a geometrical probability for grounding (hitting the wall of the channel). The ship in this model has been considered as a needle or a line, which is 1-dimensional. Does it mean that the breadth and the draught of the vessel and the depth of the channel have not been taken into the attention? Or could it be

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[1] Those who are wondering how the formula is achieved are referring to the appendix of Macduff's paper [3].

understood that hitting the wall of the channel means the draught has been exceeded the depth of the channel, and therefore it is understood that the draught and the depth has been taken into account?

He has mentioned that the model is for random grounding, which is the result of random navigation. He has also brought out that other affecting factors like fog, snow, engine failure, steering gear failure, panic, carelessness, ignorance and etc. can be applied in model by considering the Causation Probabilities. If it is so, the question is that how many factors and with which specification can be added into the model as the causation probabilities? In this case, do we really need a geometrical model to estimate the number of grounding candidates and then multiplying it by the causation probability to find the number of the ships running aground; or the affecting factors in geometrical model can be easily put into consideration as some causation probabilities?

All the above issues lead the author to come with this idea that probably the Macduff's formula could be redefined simply as a combination of different causation probabilities associated to different factors, situations or scenarios.

$$P_{RG} \propto \sum \text{or/and} \prod \mathrm{P_C} \qquad \textbf{(3.1.1.3)}$$

To make the Eq. (3.1.1.3) equal, we need to affect a constant ($0 < K \leq 1$) as a correction factor. This factor should be calculated locally and it has been suggested to consider the probable missing factors. P_{SG} or statistical probability of grounding could be a mean to obtain K value for each region (Eq. (3.1.1.4)). P_{SG} could be calculated by statistical analysis on available data about previous grounding accidents in the region. The more complete and rich database, the more accurate K value will be resulted.

$$P_{SG} \approx P_{RG} = K \times \left(\sum \text{or/and} \prod \mathrm{P_C} \right) \qquad \textbf{(3.1.1.4)}$$

where

P_{SG} is the *Statistical Probability of Grounding* associated with specific region, which should be calculated locally, according to previous and available data of groundingaccidents in that specific region

One important point about Macduff's models is that he has not directly considered the traffic density in his model. However, since he has used the statistical data for calculating the causation probability, it can be argued that the effect of traffic density has been considered into the yielded causation probability.

It is worthwhile to mention that the effect of traffic density or traffic volume can also be added into the Eq. (3.1.1.4) even by a separate causation probability, or it can be included into some other causation probabilities like time of the day.

As can be seen, the above formula is quite similar to what Macduff [3] has mentioned in his article. As a matter of fact it is, but the terms' definitions have been changed.

Second perspective

As has been mentioned, the geometrical model should present the candidate ships for grounding. In other words, it should present the probability of ships running aground while they are navigating in blind situation. Blind situation or blind navigation[1] means not doing any action to avoid grounding. If it is so, does the stopping distance (T) has any meaning in blind navigation? The ship is supposed not to do any evasive action to avoid grounding; while stopping distance means that somebody on board has did some efforts to stop the ship before going aground. However, the grounding can be avoided not only by stopping but also by changing the course. For instance, in high speed (usually more than 12 knots) the accident can be avoided more readily by turning than by stopping [28]. Also at speeds lower than 12 knots, the T (stopping distance) would be dependent on ship's own resistance and the backing thrust produced by the ship's propeller [28]. In addition, having side or bow thruster, rudder specification, loading condition, being in ballast, etc have effects on the stopping distance as well. Therefore may it be more proper to use length of the ship instead of the T? However, in this case its dependency on ship's speed will be vanished.

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[1] Some authors [3, 9, 24, 27, 33] have assumed blind navigation during their researches about maritime transportation risks. Can this assumption be really accepted? Is it possible to consider human factor as an affecting factor in causation probability by this assumption (blind navigation)? Is it feasible to analyze the associated risk of ship grounding by not assuming navigation under blind situation?

On the other hand, navigating under blind situation cannot be well defined; always there would be the risk of going aground in blind navigation, even in safe routes. For more clearness look at the Figure 9;

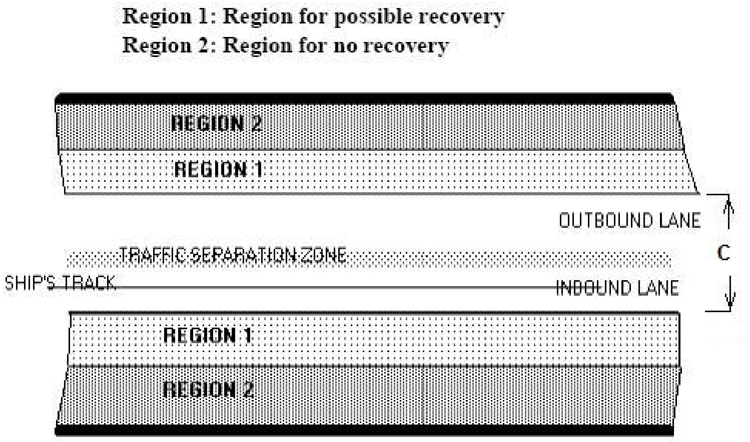

Figure 9: Hypothetical Waterway (Adapted from [4])

Always there would be risk of running aground for a ship navigating under blind situation, even for ships navigating between two region 1s (safe transit channel, inbound and outbound lanes). However, in reality those ships that have entered the region 1 are those who are candidate for going aground. If they do evasive action, they would survive however for some reasons with different probabilities, all of them will not be able to avoid entering region 2. Most probably those ships that have entered region 2 will run aground because the maneuvering ability of the ship to avoid grounding has been decreased [4]. The width of the regions 1 and 2 are depended on different parameters such as vessel's characteristics, environmental conditions etc.

Macduff's model can be modified by the help of the figure above. If we consider that C is the width of the safe transit channel (the distance between region 1s) the Macduff's P_G would be the probability of being a grounding candidate. However, in this case a new definition for T is needed. For instance, it could be defined as the distance that the vessel would travel between each position checking.

$$T = V \times a \tag{3.1.1.5}$$

where:

V is the speed of the ship
a is the average time instant between each position checking by the navigator

In this case, Macduff's model can be modified as below:

$$P_G = \frac{4(V.a)}{\pi C} \tag{3.1.1.6}$$

3.1.2 Fujii, 1974

Fujii's [2] model together with Macduff's was one of the earliest geometrical models designed for grounding, and most of the other researches in this area have been done base on their works.

Fujii has represented his model as a mean to calculate the number of strandings. He has mentioned that in his paper stranding means any kind of grounding except intentional groundings. Therefore Fujii has considered the stranding and grounding as a unique event, although his model is representing the grounding event according to the definition of this report.

Fujii's [2] grounding model is similar to his model on collision with fix object [29]; and the channel's depth and the vessels' draughts have not been considered directly for calculating the grounding candidates. Even though, he has taken the draught into consideration by mentioning that "*D is the linear cross-section of the <u>obstacle shallower than the draught</u>*".

Fujii [2] has argued that the approximate number of ships going aground in a waterway would be:

$$N = P(D + B)\rho V \tag{3.1.2.1}$$

where:

V is the average speed of the traffic flow
ρ is the average density of the traffic flow
D is the linear cross-section of the obstacle shallower than the draught
B is the ship width [*probably the average width of the ships*]

D+B	is the effective width of the obstacle or shoal
P	is the probability of mismaneuvering; (the probability of mismaneuvering in Fujii’s model can be taken as Macduff’s Causation Probability, which is a combination of important affecting factors like environmental and human factors)

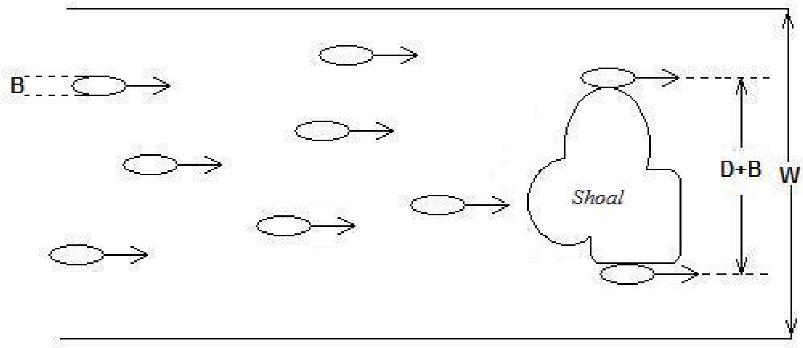

Figure 10: Grounding model; the draught is exceeding depth of the channel (Adapted from [29])

By this definition, the dimension[1] of the density of the traffic flow would be gained as:

$$[\rho] = \frac{Number\ of\ the\ ships \times T}{(L)^2} \tag{3.1.2.2}$$

if:

[N] = Number of the ships
[D] and [B] = L
[V] = L / T
[P] = *Dimensionless*

He then brought into attention that since D is usually much larger than B, B can be ignored.

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[1] *Absolute System* has been used to express the dimensions in this report. The fundamental quantities in absolute system are Length (*L*), Time (*T*), and Mass (*M*). In addition, Square Brackets [ ] are used to show that the dimension of a parameter is being presented.

$$N = PD\rho V \tag{3.1.2.3}$$

Also he has mentioned that when D is much larger than W, width of the route, the formula can be rewritten as:

$$N = PQ \tag{3.1.2.4}$$

where:

Q is the traffic volume and is equal to ρWV

If it is so, the dimension of Q (traffic volume) would be gained as:

$$[Q] = [\rho][W][V] = \frac{Number\ of\ the\ ships \times T}{(L)^2} \times L \times \frac{L}{T} = Number\ of\ the\ ships \tag{3.1.2.5}$$

However, the question is how possibly D could be larger than W? There is no point of considering an obstacle bigger than width of the waterway. In author's opinion D could be maximally equal to W and in this case all the ships would be grounding candidates.

Notwithstanding explanation above, the Eq. (3.1.2.3) can be correctly transformed to Eq. (3.1.2.4) by just replacing D with W (D is equal to W).

He also has mentioned somewhere else ([2] p.241) that "*the traffic flow density is equal to the traffic volume per unit width of waterway*", which makes the author to reach to this conclusion that the traffic volume (Q) should be equal to the product of the traffic flow density (ρ) and width of the waterway (W):

$$Q = \rho \times W \tag{3.1.2.6}$$

therefore:

$$[Q] = [\rho][W] = \frac{Number\ of\ the\ ships \times T}{(L)^2} \times L = \frac{Number\ of\ the\ ships \times T}{L} \tag{3.1.2.7}$$

On the other hand, Fujii [2] has mentioned another definition for traffic volume in his paper (p.241) as "*the product of the traffic density and the average speed*". Therefore:

$$Q = \rho \times V \Rightarrow [Q] = \frac{Number\ of\ the\ ships \times T}{(L)^2} \times \frac{L}{T} = \frac{Number\ of\ the\ ships}{L} \qquad \textbf{(3.1.2.8)}$$

Three different dimensions for traffic volume have been extracted from his paper, while he has mentioned the dimension for traffic volume as "*the number of the ships per km^2*" or

$$[Q] = \frac{Number\ of\ the\ ships}{(L)^2} \qquad \textbf{(3.1.2.9)}$$

which does not match none of them above. As is seen, there is no clear definition for traffic volume according to Fujii [2].

In author's opinion, the traffic density should be defined as the number of the ships per unit area of the waterway. However, since traffic with, for instance two small boats differs from traffic with two VLCCs[1], the dimensions of the vessels should be considered in traffic density definition. Therefore a dimensionless parameter as a size factor should be affected on the traffic density.

$$\rho = \frac{Number\ of\ the\ ships}{(W \times L)_{Waterway}} \times \overbrace{\left(\frac{(\sum(L \times B))_{Vessels}}{(W \times L)_{Waterway}}\right)}^{Size\ Factor} \qquad \textbf{(3.1.2.10)}$$

Therefore the dimension of the traffic density would be:

$$[\rho] = \frac{Number\ of\ the\ ships}{(L)^2} \qquad \textbf{(3.1.2.11)}$$

and then, with the help of mass flow rate concept in fluid dynamic, the *traffic flow rate* could be defined as (similar to one of the Fujii's definitions for traffic volume):

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[1] Very Large Crude Carrier

$$Q = \rho W V \tag{3.1.2.12}$$

where V and W are the average velocity of the vessels and the width of the waterway respectively.

If it is so, the dimension for the traffic flow rate would be gained as:

$$[Q] = [\rho][W][V] = \frac{Number\ of\ the\ ships}{(L)^2} \times L \times \frac{L}{T} = \frac{Number\ of\ the\ ships}{T} \tag{3.1.2.13}$$

Kristiansen [13] named this traffic flow rate (Q) as the "arrival frequency of meeting ships", when he was analyzing the expected number of head-on collisions in his book. However, he has not considered the size of the ships (size factor) in the used traffic density.

General believe about the Traffic Volume is the number of the vehicles passing an imaginary line during a specific period of time [30]. Therefore the Traffic Flow Rate cannot be taken as traffic volume. However, can the traffic volume be compared with a fluid dynamic concept so called flux? If it could, we define traffic volume (or traffic flux) as the numbers of vessels navigate through a unit line per unit time; or the product of the traffic density and the average speed [31], which is similar to one of the Fujii's definition for traffic volume but with different definition for traffic density.

$$\emptyset = \rho V \tag{3.1.2.14}$$

$$[\emptyset] = \frac{Number\ of\ the\ ships}{(L)^2} \times \frac{L}{T} = \frac{Number\ of\ the\ ships}{LT} \tag{3.1.2.15}$$

Since the used density in this formula has been redefined by Eq. (3.1.2.10), the size of the vessels also affects the traffic volume, and the traffic volume (traffic flux) shows the number of the vessels passing an imaginary area or a gate during specific period of time. It should be mentioned that, on contrary to fluid dynamic, the desired area is not perpendicular to the path, but is laid on the path (sea surface).

Fujii [2] has mentioned that the number of grounding is considered to fit a Poisson distribution. The Poisson distribution is a discrete probability distribution that expresses the probability of a number of events occurring in a *fixed period of time*, if these events occur with a known average rate and independently of the time since the last event.

In this regard, could the traffic flow of ships towards a shoal with the effective width of D+B (D and B have same definitions as they had in Fujii [2]) and average speed of V be defined as:

$$\varphi = \int_{T_1=0}^{T_2=T} \rho V(D+B)dt = \emptyset(D+B)T \qquad \textbf{(3.1.2.16)}$$

where:

T is the time window that the traffic flow is desired to be calculated in it.

If it is so, this calculated traffic flow can be considered as the number of grounding candidates.

$$N_G = \emptyset(D+B)T \overset{B \ll D}{\Longrightarrow} N_G = \emptyset DT \qquad \textbf{(3.1.2.17)}$$

As a result the number of grounding (N) can be calculated by affecting the probability of mis-maneuvering (causation probability):

$$N = \emptyset DT \times P_C \qquad \textbf{(3.1.2.18)}$$

It should be borne in mind that the traffic density has been considered constant during the time window for calculating the traffic flow. If the average traffic density is not used or the time window is not small enough that the traffic density could be considered constant in it, then traffic density (ρ) should be defined as a function of time:

$$\varphi = \int_{T_1}^{T_2} \rho(t)V(D+B)dt \qquad \textbf{(3.1.2.19)}$$

The question is that how easily the traffic density can be defined as a function of time? There are many factors that should be considered, like the season, day time, weather condition, economy situation, etc., which some of them are hard to predict.

Therefore, if a sort of complete database about the occurred traffic is available, it is recommended to use traffic probability density function (PDF) instead of traffic density or traffic volume. This is the mean that recently are being used by most of the researchers, as is shown in statistical models' review.

3.1.3 Kite-Powell et al., 1999

Kite-Powell et al. [7] has not expressed a geometrical model for grounding, while he has expressed his work as a mathematical model, which has been extracted from Bayes' theory[1]. Since he has not mentioned any particular situation and scenario for defining his model, his mathematical model could be used for both grounding and stranding phenomenon.

He has argued that the probability of grounding on a particular transit depends on a set of risk factors, which he has referred them as explanatory variables.

If G and S respectively denote the events that a transit results in a grounding and the event that the transit is completed safely; and also $X=(X_1, X_2, X_3, \ldots, X_p)$ represents the vector of explanatory variables, the conditional probability of G given a specific value x of X would be:

$$p(G|x) = l(x|G)p/\big(l(x|G)p + l(x|S)(1-p)\big) \tag{3.1.3.1}$$

where:

p is the unconditional probability of G

$l(x|G)$ is the likelihood of x given G

$l(x|S)$ is the likelihood of x given S

Then he has mentioned that the explanatory variables in vector X must have the attributes of the factors that contribute to the likelihood of grounding; like:

- Vessel characteristics (such as draught, beam, and maneuverability)
- Topography of the waterway (like water depth, channel width and length, complexity of turns, and traffic density)
- Environmental conditions (such as wind, visibility, currents, and waves)

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[1] Paté-Cornell [32] has used same procedure, while she was explaining the ship grounding risk for oil tankers and other cargo ships.

- Operators (experience with the vessel, training, and local knowledge)
- Information available to operators (quality of the charts and the information about tide levels and currents, VTS guidance, and navigation aids)

He argued that "*for each attribute, the explanatory variables (x_i) must be extracted from historical data as numerical or categorical indicators*"[1].

Although Kite-Powell et al.'s model does not present any number for grounding candidates; its procedure is quite useful to determine the causation probabilities. As a matter of fact, it is the exact way (using Bayesian Network and Bayes' Theory) that most of the researches have recommended to be used for estimating the causation probabilities and then the total probability of grounding.

3.1.4 Fowler and Sørgård, 2000

Fowler and Sørgård [10] are the only ones, who has separated the groundings models into powered and drift groundings. However, according to the graphical scenarios that they have mentioned for their models, it seems that (again according to the definitions of this report) their models are just well designed for stranding phenomenon and not for grounding.

Basically, their models represent the frequency of powered and drift grounding. For powered grounding:

$$f_{pg} = n_{pg}\left(P_c p_{pg,c} + P_f p_{pg,f}\right) \qquad \textbf{(3.1.4.1)}$$

where:

f_{pg} is the frequency of powered grounding (number of powered grounding accidents per year)
n_{pg} is the frequency of being in critical situation, which is defined as when a vessel track results in a way-point within 20 minutes of a landfall, where if a course change is not made a powered grounding will result
P_c is the probability of clear visibility (more than 4 km)
P_f is the probability of reduced visibility (less than 4 km)

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[1] For better understanding of how the model can be used, the readers are referring to his paper [7].

$p_{pg,c}$ is the corresponding probability of powered grounding given an critical situation in clear visibility

$p_{pg,f}$ is the corresponding probability of powered grounding given an critical situation in reduced visibility

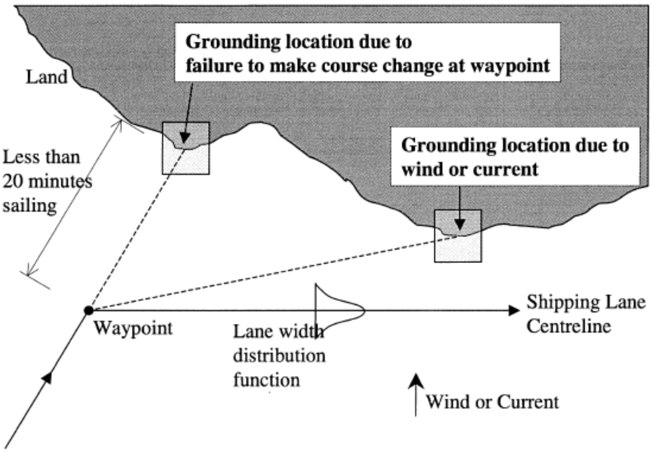

Figure 11: Powered grounding accident frequency model (Source [10])

For drift grounding:

$$f_{dg} = \sum_{l} f_{p,l} p_d \sum_{w} p_w \left[\left(1 - p_{sr,w}\right)\left(1 - p_{t,w}\right)\left(1 - p_{a,w}\right) \right] \quad \textbf{(3.1.4.2)}$$

where:

f_{dg} is the frequency of drift grounding (number of drift grounding accidents per year)

$f_{p,l}$ is the frequency of propulsion breakdown (number of ship breakdowns per year related to all lanes $\{l\}$ within 50 nm from the grounding location)

p_d is the probability of drift tracks lead to the location of grounding (drifts toward the shoreline)

p_w is the probability of the wind speed category

$p_{sr,w}$ is the probability of ship saved by self-repairing, depends on wind speeds

$p_{t,w}$ is the probability of ship saved by tow assistance, depends on wind speeds

$p_{a,w}$ is the probability of ship saved by anchoring, depends on wind speeds

Fowler and Sørgård have used FTA for calculating the probability of collision and grounding in given critical situations[1].

It should be considered that the probabilities of ship rescued by any of the presented methods (self-repair, anchoring, tug assistance) are also conditional to the location, where the ship has been breakdown and also the drift speed. Since the drift speed is related to the wind speed, they have correctly mentioned that the probability of rescue is conditional to the wind speed.

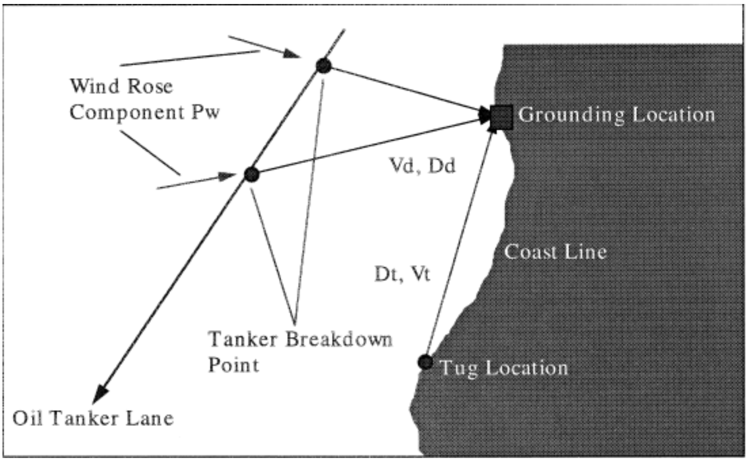

Figure 12: Drift grounding accident frequency model (Source [10])

In the drift grounding model, they have assumed that the current and wind are constant throughout the drift period, which can decrease the accuracy of the model for longer drift times.

One interesting point about Fowler and Sørgård's [10] drift grounding model is that they have brought into attention the total time that would take to repair the failure in the ship, or the emergency tow assistance receives. They have correctly assumed that if the ship's crews would be able to repair the mechanical problem during a period of time and in a certain distance from the shore or the tow assistance would arrive during that time, the grounding probability will decrease. Also, anchoring can decrease the drift grounding

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[1] Readers are referring to their paper [10] for better understanding of the way of calculation.

probability; however it depends on different factors and situations like the seabed composition.

Fowler and Sørgård's article showed that the grounding situations can be defined precisely likewise the domain and encounter in collision. Therefore by having exact definitions for "being in grounding situation" the geometrical probability and also the causation probabilities could be defined and calculated easily. However, it should be borne in mind that having specific international definitions will avoid of different interpretations and different results. Nevertheless, it is possible that the definitions for "being in grounding situation" differ from region to region or case to case. In such a case, it is necessary to express the exact used definition for "being in grounding situation" (like Fowler and Sørgård) to show how the calculations have been done. For instance, critical situation in their drift grounding model has been defined as the number of ship-hours spent within 50 nm of the shoreline, multiplied by the probability that the ship drifts toward the shoreline.

3.1.5 Kristiansen, 2005

Kristiansen is the only one who has distinguished grounding from stranding. As has been mentioned before, grounding and stranding in this report have been defined based on his definitions for these two events.

Kristiansen [13] grounding model could be considered as a simple combination model of Fujii's [2] and Macduff's [3] models. He has first tried to find the probability of a vessel hitting an obstacle in a fairway; and has then calculated the probability of grounding per passage of the fairway by multiplying the achieved probability by the causation probability.

He has assumed that the vessel continues on an unchanged straight course in critical phase. Critical phase could be defined as when the ship has lost her control due to technical or human error or both, and also when the width of the waterway, in which the ship is navigating, has been limited by some obstacles. The ship's lateral and longitudinal positions at the time of critical phase have been assumed to be random.

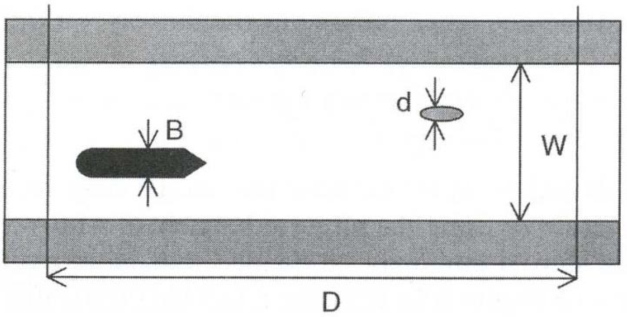

Figure 13: Modeling of a grounding accident (Source [13])

Therefore he has related the probability of the vessel hitting the obstacle to the dimensions of the waterway and the breadth of the ship.

$$P_i = \frac{B + d}{W} \tag{3.1.5.1}$$

where:

W is the average width of the fairway
d is the cross-section of the obstacle, e.g. shoal, rock, island, etc.
B is the breadth of the vessel

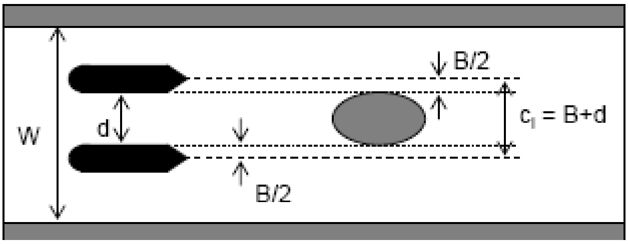

Figure 14: Characteristic parameters of the grounding situation (Source [13])

If there are number of obstacles presented in the fairway, the breadth of the critical corridor (B+d), in Figure 14, would be the breadth of the vessel plus the union of the cross-section of the obstacles:

$$P_i = \frac{1}{W} \times \left[B + \left(d_1 \bigcup d_2 \bigcup \dots \bigcup d_k\right)\right] \tag{3.1.5.2}$$

or if there were no overlaps between the obstacles, Eq. (3.1.5.2) would be easily expressed as:

$$P_i = \frac{1}{W} \times \left[B + \sum_k d_k \right] \tag{3.1.5.3}$$

and if the density of obstacles in the waterway be assumed as ρ (obstacles/area-unit), the number of obstacles (k) would be calculated as:

$$k = \rho \times D \times W \tag{3.1.5.4}$$

where:

D is the length of the channel or a section of the fairway, where the obstacles located

Therefore by replacing Eq. (3.1.5.4) in Eq. (3.1.5.3), the probability of hitting the obstacle (grounding) would be calculated as:

$$P_i = \frac{1}{W} \times (B + \rho \times D \times W \times d) = \frac{B}{W} + \rho \times D \times d \tag{3.1.5.5}$$

or if the ship’s breadth (B) is considered small relative to the width of the channel (W), Eq. (3.1.5.5) can be rewritten as:

$$P_i = \rho \times D \times d \tag{3.1.5.6}$$

However, since the right hand sides of the above equations [Eq. (3.1.5.5) and Eq. (3.1.5.6)] are not dimensionless, the resulted probability would not be dimensionless, while it should be.

$$[P_i] = \frac{Number\ of\ Obstacles}{L^2} \times L \times L = Number\ of\ Obstacles \tag{3.1.5.7}$$

Kristiansen then has mentioned that the model's validity can be improved by affecting the actual maritime traffic distribution into the model. Therefore, the position of the vessels can realistically be described with the help of the actual traffic distribution in a lane, instead of the physical barriers of the fairway.

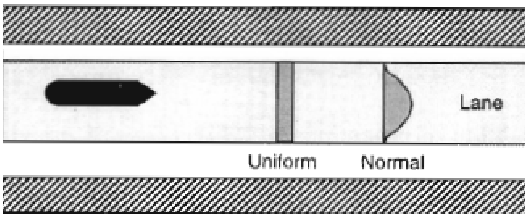

Figure 15: Enhanced grounding scenario (Source [13])

Kristiansen is the only one, who has clearly distinguished the difference between stranding and grounding accidents:

"*Recalling the straight line fairway scenario in the previous section* [Grounding], *there is also a risk of stranding. The term stranding is used for the impact with the shoreline in contrast to the impact with individual shoals and islands in the fairway.*"

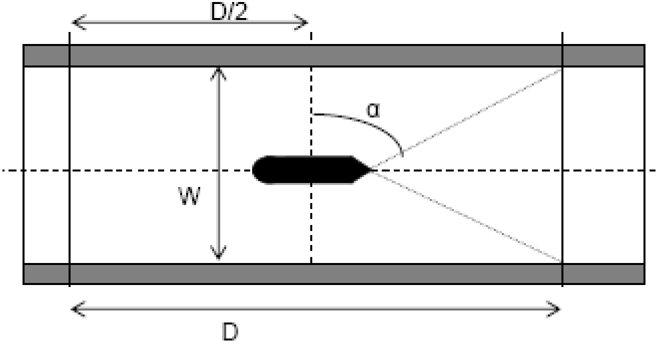

Figure 16: Stranding model (Source [13])

He has assumed that in the case of loss of control, the vessel may continue on any course ahead. The critical angle for the vessel that might end up with stranding is α. Therefore the conditional probability of stranding would be the ratio of the critical angle over the total angle for one lateral side:

$$P_i = \frac{\alpha}{\pi/2} = \frac{\tan^{-1}\left(\frac{D/2}{W/2}\right)}{\pi/2} = \frac{\tan^{-1}\left(\frac{D}{W}\right)}{\pi/2} \quad \textbf{(3.1.5.8)}$$

The arctangent term can be replaced by an expression of Taylor expansion series[1] as:

$$P_i = \frac{\pi/2 + \sum_n (-1)^n \frac{(W/D)^{2n-1}}{2n-1}}{\pi/2} = \frac{2}{\pi} \times \left[\frac{\pi}{2} - \frac{W}{D} + \left(\frac{W}{D}\right)^2 - \left(\frac{W}{D}\right)^3 \dots\right] \quad \textbf{(3.1.5.9)}$$

It is assumable that the length of the waterway (D) is much greater than its width (W); therefore the terms of W/D with power more than one can be neglected. As a result, the conditional stranding probability would be simplified as:

$$P_i = 1 - \frac{2}{\pi} \times \frac{W}{D} \quad \textbf{(3.1.5.10)}$$

Kristiansen then has argued (like Fowler and Sørgård [10]) that the "*average time to regain vessel control and thereby selection of fairway section distance* [or the length of the channel (D)] *has a vital impact on the estimated probability*"

Nevertheless, the models presented by Kristiansen [13] are too simple to be used for real cases. He mentioned that the models are used for comparing alternatives, and the probabilities calculated by these models cannot be used for real world scenarios as precise numbers.

3.2 Statistical Models

The models that are presented in this part are:

- Pedersen, 1995
- Somonsen, 1997

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[1] CliffsNotes.com. *Taylor Series*. 19 Mar 2009 <http://www.cliffsnotes.com/WileyCDA/CliffsReviewTopic/topicArticleId-19736,articleId-19727.html>.

- Karlsson et al., 1998
- Otto et al., 2002
- Rambøll Danmark A/S, 2006
- Gucma, 2006
- Quy et al., 2007

3.2.1 Pedersen, 1995&Simonsen, 1997

Pedersen’s model [33] is the most used model in recent years. Almost all of the recent risk analysis and calculations for collision and grounding were based on his model. Also Simonsen’s model [34] is a revised version of Pedersen’s work. Their models have been used in two recent risk analysis software (GRACAT [35, 36] and GRISK[37]) for analyzing grounding and collision risks.

Pederson and Simonsen have not mentioned whether their models are suitable for grounding or stranding. However, since their models are based on the integration of probability density function of ships’ traffic over the boundaries of the obstacle, it can be argued that their models are suitable for both grounding and stranding according to this report’s definitions.

Like Fujii’s [2], Pedersen’s [33] model gives the number of groundings, and not the probability of grounding as Macduff’s [3] does. However, on the contrary, Pedersen has considered the time factor in his model. It means that the Pedersen’s model will estimate the expected numbers of grounding per year or grounding frequency.

Pedersen has defined an imaginary route with a bend in the navigation route around an area where ships with a draught above a certain level may ground. Does it mean that he has considered the ship’s draught and the depth of the channel in his model? If it is so, regarding to previous definitions and models also, do we really need to think about how these factors (draught and depth) can affect the model? Or going aground, itself, means that those factors have been considered into the model?

He has categorized the grounding/collision scenarios into 4 different categories as:

Cat.1 Ships following the ordinary, direct route at normal speed. Accidents in this category are mainly due to human error, but may include ships subject to unexpected problems with the propulsion/steering system which occur in the vicinity of the fixed marine structure or the shoal.

Cat. 2 Ships which fail to change course at a given turning point near the obstacle

Cat.3 Ships which take evasive action in the vicinity of the obstacle and as a result, collide with structure or ground on the shoal

Cat. 4 All other track patterns than Cat. 1, 2, 3, e.g. off-course ships and drifting ships

Therefore the estimated frequencies of grounding on the shoal can be obtained as a sum of the four different accident categories.

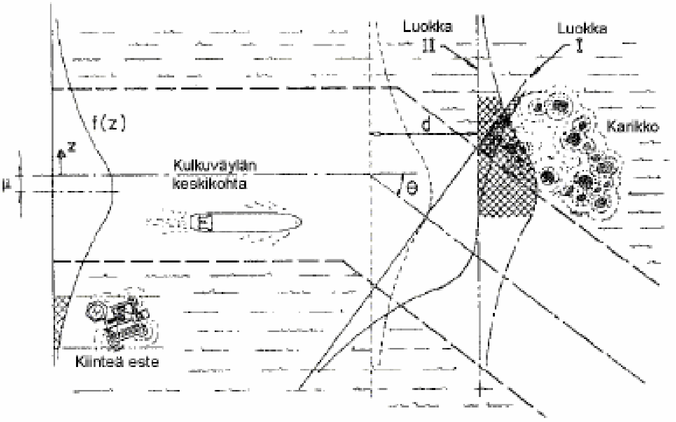

Figure 17: Distribution of ship traffic on a navigation route (Source [33])

The simplified expression for the two first categories, which most of the happened accidents are categorized into them [34], would be expressed as:

$$F_{Cat.1} = \sum_{Ship\ class\ i=1}^{n\ class} P_{Ci} Q_i \int_L f_i B_i ds \tag{3.2.1.1}$$

$$F_{Cat.2} = \sum_{Ship\ class\ i=1}^{n\ class} P_{Ci} Q_i P_0^{(d-a_i)/a_i} \int_L f_i B_i ds \tag{3.2.1.2}$$

where

F_{Cat}	is expected number of collision or grounding per year
i	is the number of ship class determined by vessel type and dead weight tonnage or length
P_{ci}	is the causation dependents on vessel class (i) by the effect of the pilot since the probability of having a pilot during the passage increase with the vessel size
Q_i	is the number of movements per year of vessel class (i) in the considered lane
L	is the total width of considered area perpendicular to the ships' traffic
f_i	is ship track distribution
B_i	is the collision indication function, which is one when the ship strikes the structure or shoal and zero when the candidate colliding ship does not hit the obstacle, that is, passes safely or grounds prior to collision or grounding on the considered shoal[1].
P_0	is the probability of omission to check the position of the ship
d	is the distance from obstacle to the bend in the navigation route, varying with the lateral position of the ship
a_i	is the average length between position checks by the navigator

Pedersen has considered the traffic distribution over the transverse section of the waterway (f_i) instead of using traffic volume or traffic density in his model. Nowadays this probability density function, which mostly considered as a Gaussian distribution, and its parameters can be estimated easily from statistical databases collected by VTS (Vessel Traffic Services) centers. However, in case of lack of data, it can be simply assumed as a Gaussian distribution and its parameters can be approximated.

The other advantage of his model is that he has clearly put into account the ship classes, which he has related them to vessel type and DWT or length.

One of the interesting points about his model is that he is the first one who has tried to somehow put a human factor in geometric model of collision/grounding. The P_0 is the probability of omission to check the position of the ship, which is connected to human factors.

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[1] The question is how the grounding on shoal and colliding with shoal can be distinguished from each other? In author's point of view, these two events should be classified as grounding.

The factor B in Pedersen’s model has a complicated definition. According to correspondence between the author and Ms. Maria Hänninen, since there would be no point of integrating ship track distribution (f_i) over the total width of the considered area perpendicular to traffic (L), because not all the ships in the lane are grounding or collision candidates, the B-function has been defined to restrict the integration for the ships on grounding or collision course only. However, it is probable that someone like the author of this review, understands from Pedersen’s definition that B would be zero for all grounding candidates (if striking the shoal would not be categorized as grounding), and since B is inside the integral, the number of groundings would be always zero by this definition!

In comparison, Simonsen [34] has modified the Pedersen’s model in his Doctorate thesis. He has used the same imaginary route as Pedersen used; but has defined the grounding frequency for two first categories as:

$$N_I = \sum_{Ship\ class\ ,i} P_{C,i} Q_i \int_{Z_{min}}^{Z_{max}} f_i(z) dz \tag{3.2.1.3}$$

$$N_{II} = \sum_{Ship\ class\ ,i} P_{C,i} Q_i e^{-d/a_i} \int_{Z_{min}}^{Z_{max}} f_i(z) dz \tag{3.2.1.4}$$

where:

a_i	is the average distance between position checks by the navigator (assumed to be 75% of the ship’s length while she is in the channel; and set to one ship length while she is between the channel and the harbor)
d	is the distance from obstacle to the bend in the navigation route, varying with the lateral position, s, of the ship
i	is the index for ship class, categorized after vessel type and dead weight or length
$f_i(z)$	is the probability density function for the ship traffic
$P_{c,i}$	is the causation probability, i.e. ratio between ships grounding and ships on a grounding course
Q_i	is the number of ships in class *i* passing a cross section of the route per year
F_{Cat}	is expected number of collision or grounding per year

z is the coordinate in the direction perpendicular to the route
(z_{min}, z_{max}) are the transverse coordinates for an obstacle

As is seen, Simonsen has replaced the B factor by integration boundaries as Z_{Max} and Z_{Min}. In this way, the unclear role of the B has been replaced by the clear definition of integration boundaries. Therefore, Simonsen's model could be used even for calculating collision frequency or grounding frequency; and the integration boundaries let us to consider those ships that are in grounding or collision courses only (Figure 18).

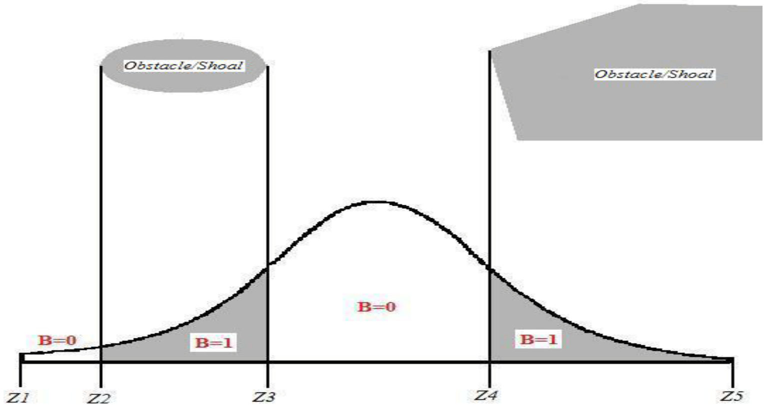

Figure 18: Pedersen's B factor and Simonsen's integration boundaries

Simonsen assumed that the event of checking the position of the ship can be described as a Poisson process. Therefore the term e^{-d/a_i} is representing the probability of the navigator not checking the position of the vessel. He has also mentioned that the causation probability (P_C) can be estimated by the help of available accident data collected at various locations and then transformed to the study region; or it can be found by the help of Fault Tree Analysis (FTA).

He has then mentioned that the theoretical result achieved by the model is quite sensitive to both the causation probability, P_C, and the distance between each position checking, a_i.

3.2.2 Karlsson et al., 1998

Karlsson et al. [38] has defined a model for grounding in Øresud link between Malmö in Sweden and Copenhagen in Denmark. The model will just yield the grounding probability due to human failure as (see Figure 19):

$$P(Grounding\ at\ point\ E) = P_{human} \times \frac{\min\,(d; l - d')}{l} \qquad \textbf{(3.2.2.1)}$$

where:

l	is taken as 4 nm
P_{human}	is taken as 2.0 E-04 according to [29]
d and d'	are defined in Figure 19

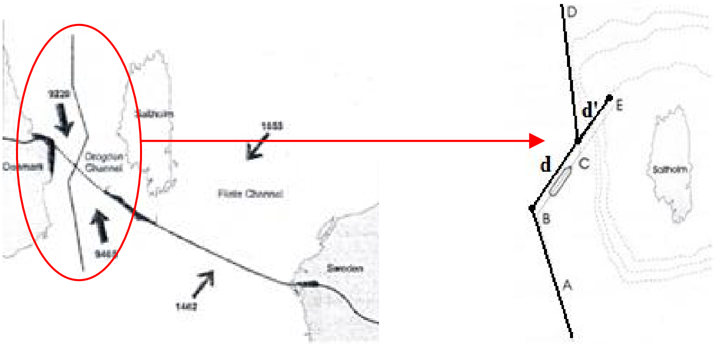

Figure 19: Possible grounding scenario due to human failure in Øresud link (Adapted from [38])

One interesting point about his model is that he has mentioned that the distribution of the ship traffic teraservers to the navigation channel can be assumed as a combination of uniform and normal distributions, as 2% uniform and 98% Gaussian. (Figure 20) Although he has not mentioned that how he has come with this conclusion, it is probable that this conclusion was extracted from the used database for traffic distribution.

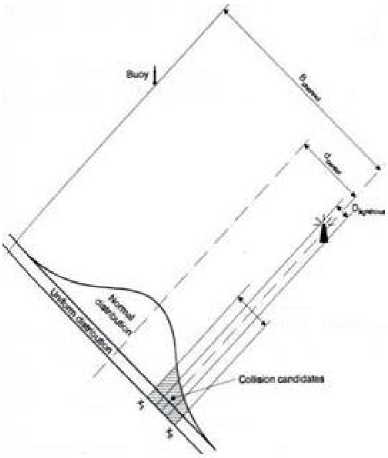

Figure 20: Transverse distribution of grounding candidates (Source [38])

He also has mentioned that the probability of grounding for those ships that used pilots is more or less similar to the others, which is quite different from general belief about presence of pilots.

3.2.3 Otto et al., 2002

The procedure for calculating the risk of grounding, presented in Otto et al. [16], is quite similar to the collision with rocks or coral-reefs. It can be said that it is a simplified version of Pedersen's model. Therefore it can be concluded that his model, same as Pedersen's, is suitable for both grounding and stranding.

The distribution of routes over the traffic lane was assumed to be normally distributed and therefore the grounding probability would be calculated by integration of route probability distributions that overlapped with the obstacle. This model, like Pedersen [33] and Simonsen [34] will yield the annual frequency of the grounding.

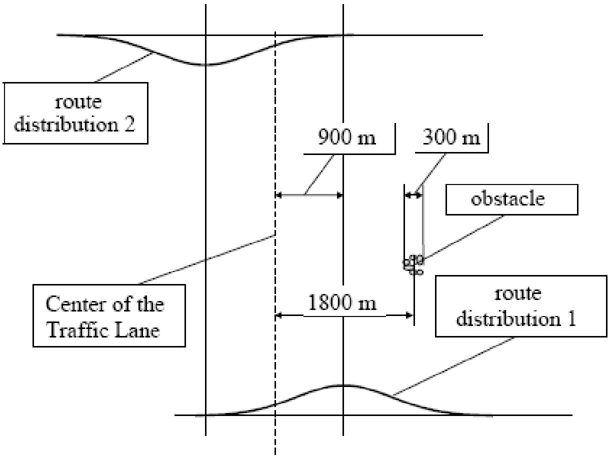

Figure 21: Sample grounding scenario (Source [16])

$$f_G = n_v P_{cg} (P_{G1} + P_{G2}) \tag{3.2.3.1}$$

where:

n_v	is the number of voyages per year
P_{cg}	is the causation factor
P_{G1}&P_{G2}	is the grounding probability of ships navigating in route 1 and 2 respectively. Those are calculated by integration of route probability distributions that overlapped with the obstacle.

3.2.4 Rambøll Danmark A/S, 2006

One other interesting existing risk model for grounding has been presented by Rambøll Danmark A/S [39] in August 2006. The model has been presented in a report about the navigational safety in a sound between Denmark and Sweden named Øresund. The parties, who had contribution in the study, were the Royal Danish Administration of Navigation and Hydrography, the Danish Maritime Authority and the Swedish Maritime Administration.

It can be argued that the presented model in the report is again a simple deduction from Pedersen's model. It also, same as Pedersen, yields the frequency of grounding.

One interesting point about their work is that they argued that the collision with fixed obstacle can be interpreted as grounding on a zero water depth curve. Therefore, they have used same model for both grounding and collision with a fixed obstacle. In this report's point of view, it can be concluded that the model is designed for both grounding (collision with fixed obstacle) and stranding.

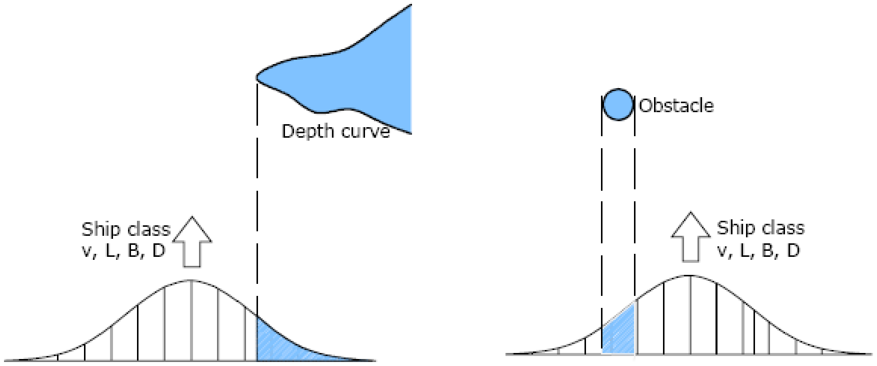

Figure 22: **Stranding (left) / Grounding (right) candidates for ships on straight route (Source [39])**

They have separated the event into two different scenarios according to the nature of the navigation route.

1. Straight route before meeting shoal or obstacle, which means all ships at grounding course not making an evasive maneuver are grounding candidates

2. Bend on the route before meeting shoal or obstacle, which means all ships on grounding course before the bend not making a turn in the bend are grounding candidates

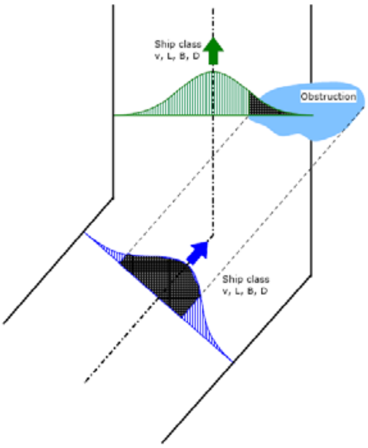

Figure 23: Grounding candidates for ships on a route with a bend (Source [39])

In fact, the second scenario (Figure 23) is a combination of two first scenarios (Figure 22). Therefore, when the grounding frequency is calculated for the second scenario, the grounding frequency in two (or even more) different situations should be calculated separately and then combined together to give the final grounding frequency.

The grounding frequency would be calculated by the formula below:

$$f_{grounding} = N_Q \times (1 - P_{evasive}) \qquad \textbf{(3.2.4.1)}$$

where:

N_Q	is the number of grounding candidates
$1\text{-}P_{evasive}$	is the probability of not making an evasive maneuver due to human or technical failures

The model seems simple at the first glance; however calculating its parameters, same as for others' models, is not a simple task.

The number of grounding candidates (N_Q) would be gained by the help of ship traffic distribution, which for the mentioned location it has been assumed that it fits a combination of uniform and normal distribution[1]. The parameters of the

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[1] Like what Karlsson et al. [38] has recommended.

traffic distribution could be gained by analyzing the AIS data. The research team has mentioned that the factors that have effect on $P_{evasive}$ are:

1. Number of ships presented in the location
2. Pilot on board
3. Speed distribution for ships
4. Draught distribution for ships
5. Ship type distribution for each direction
6. Location of shoal or obstacle
7. Water depth at shoal or obstacle
8. Distance from bend to shoal or location

As is seen, the affecting parameters are not few. Besides, defining each of the above factors requires analyzing a quite huge amount of data. The analyzing team has used BN to analyze the above parameters[1].

3.2.5 Gucma, 2006& Quy et al., 2007

Quy et al. [40] has defined a model with the help of a graphical explanation that Gucma [41] has used for his real time simulation. The model, like Macduff's [3], has yielded the probability of a ship exceeding from a certain waterway width, or in other words, hitting the wall of the channel. Therefore, Quy's and Gucma's models are giving the probability of stranding, according to the definition of this report. However, it seems that their models can be modified to be used to calculate the probability of grounding as well.

Quy et al. [40] has mentioned that the probability of a ship exceeding from a certain waterway width can be determined as:

$$P_{ex} = P(y > D_r | Env = i) = \int_{B/2}^{\infty} f(y)dy \qquad \textbf{(3.2.5.1)}$$

where:

D_r is the half of the channel width
B is the breadth of the ship

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[1] The readers are referring to the report [39] for detailed used BNs.

f(y)	is the density function of the ships extreme positions (port and starboard of the ship) in respect to the center of the waterway width in the simulation of a maneuvering scenario i^{th}
i	is the maneuvering scenario, which is the different combinations of environmental conditions affecting the ship's maneuverability. They are divided into various classes known here as "maneuvering scenarios"

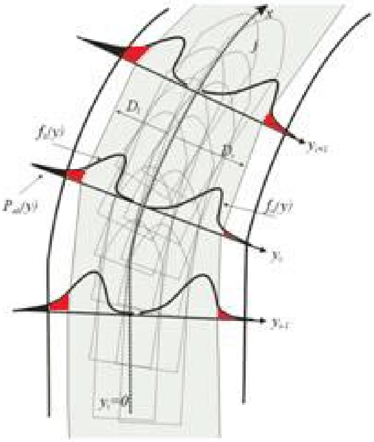

Figure 24: Distribution of ship's position based on the simulation results (Source [41])

Therefore the probability of ship exceeding the waterway section borders during a given time period can be determined as:

$$P_{life} = N_{ship} \sum_{i=1}^{N_e} P_{ex} P_{oc} [Env = i] \tag{3.2.5.2}$$

where:

N_{ship}	is the number of ships present in the waterway during a given time period
N_e	is the number of scenarios
$P_{oc}[Env=i]$	is the occurrence frequency of the maneuvering scenario i^{th}

In comparison, Gucma [41] has presented the probability of accident due to safe waterway exit as:

$$P_a = \int_{d_{max}}^{+\infty} f(y)dy \qquad \textbf{(3.2.5.3)}$$

where:

$f(y)$ is the density function of ship extreme positions
d_{max} is the distance from the waterway center to its border

As it is seen, the two authors do not have the same idea about the integration's lower boundary. The Gucma's gives the probability of ship's accident (stranding), which are the black zones in Figure 24; while it seems that the Quy's does not present anything meaningful.

F(y) is the function of the channel's width, which shows the locations of the extreme starboard and port points of the ship with regard to the width of the channel. Because the lateral location of the ship is not fixed, the breadth of the ship (B) cannot be considered as a constant value for integration; and therefore the breadth of the ship, itself, is somehow a variable in this function and cannot be considered as a boundary for integration[1].

However, the author of this report assumes that by using the presented theory in [4] (see Figure 9), the lower integration boundary in above equations [Eq. (3.2.5.1) and Eq. (3.2.5.3)] can be considered as D_r or D_l, which are the right and left boundaries of safe maneuvering area of the waterway (outer borders of regions 1, refer to Figure 9). By this assumption, the result will show the probability of the ship to be a grounding candidate[2] or entering the no-recovery area (Figure 9). Therefore the Eq. (3.2.5.1) can be rewritten as:

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[1] It means that the extreme position of the starboard and port of the ship (B/2) with regard to the centerline of the waterway is not fixed, and it cannot be considered as an integration boundary.

[2] Entering the regions 2 refer to Figure 9, or black and red zones in Figure 24.

$$P_{ex} = P\big((y > D_r)\big|Env = i\big) = \int_{D_{r,l}}^{\infty} f(y)dy \qquad \textbf{(3.2.5.4)}$$

The most important feature of Quy et al.'s model [40], which makes it different from other models, is that he has used different combination of environmental conditions as scenarios instead of using causation probabilities. He has taken into attention different scenarios that can occur for the ship while she is on the sea. However, he has rejected undesired combination of environmental conditions like the combination of very low wind speeds but very high waves or windy situation with fog, which have hardly ever occurred.

Moreover, in the graphical model that has been used by Gucma [41], the center line of the ship has not been used to define the distribution of the ships' positions. On the contrary the extreme positions of starboard and port sides of the ship have been considered, which is more realistic in order to model the stranding event as an event of hitting the wall of the channel. It should be mentioned that Gucma [42] has expressed the model briefly for the first time in one of his paper in year 2000, where he has put into word the terms *technical reliability* and *navigation reliability* to talk about the effects of navigation device failures and human factor, respectively.

4. Conclusion

“*Learning and unlearning are vital factors in the implementation of new concepts. Implementation requires two vital things; Change-radical shifts in conditions- and Transition-the human process of getting used to change. The transition takes time*” (Dag Ericsson) [43]

One of the main issues in SGRA is that by today’s knowledge, a holistic and precise model which could describe the reality, if not say impossible, at least is a really hard goal to achieve. Nevertheless, the main questions are:

- Is such model really needed to calculate the risk of grounding?
- What precision should the model have to deliver an acceptable level for grounding risk assessment?

By reviewing the literature, the author has come to this idea that since the causation probabilities cannot reveal the features of the traffic and the geometrical locations of the ships and obstacles, having a geometrical model would be necessary for SGRA. Now the question is:

- How general this geometrical model should be?

The author believes that since the geometrical model should be used generally for all locations and situations (scenarios), it should contain as few parameters as possible. It means every factor that its value may change if the scenario (not the location) is changed, should not be considered in risk analysis as geometrical model. However, they should be added into the analysis as causation probability. Then the causation probability could be defined locally as a general causation probability, which contains the specific conditions of the accident that may occur.

One another possible view is to define different causation probabilities, which each of them is connected to specific event or situation. For instance one causation probability connected to the time of the day (being day or night) and the other one connected to presentation of pilot on board and so on. They should be defined as universal causation probabilities, which are valid for the same situation all over the world. For calculating a total (local) causation probability for a specific scenario, all different probabilities for the applied situations should be known and then they can be combined together to reach to a unique causation probability for a unique scenario. Then when it multiplied by the geometrical probability that gained from the geometrical model, it can give us the final probability of grounding in specific location and situation.

As it is seen in different reviewed models, the causation probabilities could be defined and calculated either by Fault Tree Analysis (FTA) or Bayesian Network Analysis (BNA) or even a combination of these two methods, which is recommended by the author.

It is also worthwhile to mention that traffic distribution is one of the main factors that should be included in geometrical model. However traffic distribution, itself, depends on some other factors like time of the year (season). Although it is possible to use average traffic distribution for the whole year, it is recommended to use a suitable time window (ex. seasonal) for the analysis, in which the traffic distribution is somehow constant. Since seasonal traffic distribution fluctuation for GOF is high, at least this precise time window is vital for the GOF.

Another interesting point about the reviewed literature is that in all models, the ship’s draught and the depth of the waterway have not been directly considered in the models. However, the grounding accident has been defined when the draught exceeds the depth. Does it mean that there is really no need to take into account the draught and the depth when the model is being designed? Could not a model be defined, in which the depth and the draught both are considered directly into it?

Moreover, it should be mentioned that although the term “grounding candidate” has been explained as “those ships that would most probably go aground if nothing, internally or externally, changes”, author believes that there would be more clear estimation about the grounding candidates with the exact information about the near-miss cases.

Near-miss cases are those ships that were near to have an accident (go aground in this case) but survived by just a minute. They occur in situations that control measures are postponed until the last minute, or where the technological capacities suddenly fail [44]. Although some efforts have been done to prepare a database about the near-miss cases, since most of the navigator officers are not eager to admit that there was anything special about the incident, the near-miss grounding situations have not been registered in any databases yet [15, 26].

It is worthwhile to mention that in spite of the collision accidents, which “*being in encounter situation*” could be defined easily (when two or more ships meet each other), definition of “*being in a grounding situation*” might not be so clear. Although, Fowler and Sørgård [10] and Amrozowicz [4] have somehow defined the grounding situations, still there is a need for an international definition.

5. Further Researches

"If we knew what we were doing, it wouldn't be called research, would it?" (Albert Einstein)

Since this literature review has been carried out specifically for GOF, and the aim was to find a suitable risk model for ship grounding in GOF; these further researches are recommended for SGRA in GOF.

Recommended further researches:

1. Choose and modify an existing geometrical model or define a new geometrical model for the ship grounding probability in GOF.
2. Clarify the specific features of shipping in GOF, which have effect on the probability of ship grounding in the region
3. Calculate or define the causation probabilities connected to each specific features of GOF
4. Calculate the total probability of ship grounding in the GOF for current traffic situation
5. Validate the gained result by comparing with available statistical data
6. Predict and calculate the total probability of ship grounding in the GOF for traffic situation up to year 2015

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7. Appendix

Collected values for Grounding Causation Probability

Reference	***Value of P_C***		***Location***	***Remarks***
Macduff, 1974 [3]	1.55E-04		North Sea, Dover Strait	without traffic separation scheme
	1.41E-04			with traffic separation scheme
Fujii, 1974 [2]	$\log P = -3.7 \pm 0.4$	1.26E-04	Uraga Strait	Probability of mis-maneuver
		5.01E-04	Hiraiso, Akashi Channel	Ship Size (GRT) >500
		6.31E-04		Ship Size (GRT) 100-500
		1.00E-04		Ship Size (GRT) 20-10
		1.00E-03	Sementoiso, Akashi Channel	
		3.16E-04	Bisanseto, Ozeishima Island	100-500 GRT
		2.00E-04		>500 GRT
		3.16E-04		<100 GRT
		6.31E-05	Naruto Strait, Nakaze bars	
Pedersen, 1995 [33]	1.59E-04			
Simonsen, 1997 [34]	3.50E-04			
Kite-Powell et al., 1999 [7]	3.53E-04	0.0019	New York/ New Jersey	good vis. >=2 km, Small T<30ft, US flag
		0.0002		good vis. >=2 km, Small T<30ft, non-US flag
		4.50E-03		good vis. >=2 km, Large T>=30ft, US flag

Kite-Powell et al., 1999 [7]	3.53E-04	0.0015	New York/ New Jersey	good vis. >=2 km, Large T>=30ft, non-US flag
		0.0002		good vis. >=2 km, Barge Trains
		0.007		poor vis. < 2 km, Small T<30ft, US flag
		0.0014		poor vis. < 2 km, Small T<30ft, non-US flag
		0.0937		poor vis. < 2 km, Large T>=30ft, US flag
		0.0139		poor vis. < 2 km, Large T>=30ft, non-US flag
		0.0015		poor vis. < 2 km, Barge Trains
		0.002		low wind <10 m/s, Small T<30ft, US flag
		0.0002		low wind <10 m/s, Small T<30ft, non-US flag
		0.0066		low wind <10 m/s, Large T>=30ft, US flag
		0.0018		low wind <10 m/s, Large T>=30ft, non-US flag
		0.0002		low wind <10 m/s, Barge Trains
		0.002		high wind>=10 m/s, Small T<30ft, US flag
		0.0008		high wind>=10 m/s, Small T<30ft, non-US flag
		0.005		high wind>=10 m/s, Large T>=30ft, US flag
		0.001		high wind>=10 m/s, Large T>=30ft, non-US flag
		0.0002		high wind>=10 m/s, Barge Trains
	1.64E-03	0.0023	Tampa Bay	good vis. >=2 km, Small T<30ft, US flag
		0.0008		good vis. >=2 km, Small T<30ft, non-US flag
		0.0048		good vis. >=2 km, Large T>=30ft, US flag
		0.0016		good vis. >=2 km, Large T>=30ft, non-US flag

Kite-Powell et al., 1999 [7]	1.64E-03	0.0017	Tampa Bay	good vis. >=2 km, Barge Trains
		0.0125		poor vis. < 2 km, Small T<30ft, US flag
		0.0072		poor vis. < 2 km, Small T<30ft, non-US flag
		0.0407		poor vis. < 2 km, Large T>=30ft, US flag
		0.016		poor vis. < 2 km, Large T>=30ft, non-US flag
		0.017		poor vis. < 2 km, Barge Trains
		0.0024		low wind <10 m/s, Small T<30ft, US flag
		0.0009		low wind <10 m/s, Small T<30ft, non-US flag
		0.0053		low wind <10 m/s, Large T>=30ft, US flag
		0.0018		low wind <10 m/s, Large T>=30ft, non-US flag
		0.0019		low wind <10 m/s, Barge Trains
				high wind>=10 m/s, Small T<30ft, US flag
				high wind>=10 m/s, Small T<30ft, non-US flag
				high wind>=10 m/s, Large T>=30ft, US flag
				high wind>=10 m/s, Large T>=30ft, non-US flag
		0.0048		high wind>=10 m/s, Barge Trains
	1.15E-03	0.0014	Houston/Galveston	good vis. >=2 km, Small T<30ft, US flag
		0.0003		good vis. >=2 km, Small T<30ft, non-US flag
		0.0051		good vis. >=2 km, Large T>=30ft, US flag
		0.0009		good vis. >=2 km, Large T>=30ft, non-US flag
		0.0012		good vis. >=2 km, Barge Trains
		0.0139		poor vis. < 2 km, Small T<30ft, US flag

Kite-Powell et al., 1999 [7]	1.15E-03	0.0026	Houston/Galveston	poor vis. < 2 km, Small T<30ft, non-US flag
		0.0429		poor vis. < 2 km, Large T>=30ft, US flag
		0.0013		poor vis. < 2 km, Large T>=30ft, non-US flag
		0.01		poor vis. < 2 km, Barge Trains
		0.0016		low wind <10 m/s, Small T<30ft, US flag
		0.0004		low wind <10 m/s, Small T<30ft, non-US flag
		0.0057		low wind <10 m/s, Large T>=30ft, US flag
		0.0009		low wind <10 m/s, Large T>=30ft, non-US flag
		0.0014		low wind <10 m/s, Barge Trains
				high wind>=10 m/s, Small T<30ft, US flag
				high wind>=10 m/s, Small T<30ft, non-US flag
		0.0745		high wind>=10 m/s, Large T>=30ft, US flag
				high wind>=10 m/s, Large T>=30ft, non-US flag
		0.0041		high wind>=10 m/s, Barge Trains
Fowler & Sørgård, 2000 [10]	3.07E-04		North Sea Area	Powered, good visibility
	2.47E-04			Powered, good visibility, within VTS zone
Fowler & Sørgård, 2000 [10]	8.57E-04		North Sea Area	Powered, poor visibility
				Powered, poor visibility, within VTS zone
Otto, 2002 [16]	1.59E-04			Taken from Pedersen [33]

Kristiansen, 2005 [13]	2.00E-04		Mean value of others' values (0.80E-4 to 3.30E-4)

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