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Application of Probabilistic Damage Stability for Risk Reduction Related to Cruise Ship Operation in Arctic

A Risk Based Approach

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PREFACE

This Master Thesis work has been carried out at the Department of Marine Technology at the Norwegian University of Science and Technology, NTNU, during the spring semester 2015. This thesis is the final step towards my M.Sc. degree, where my specialization lies within Marine System Design.

Before starting my thesis work, I had limited knowledge about the risk level of ship operation in Arctic and the use of probabilistic damage stability. Extensive amount of time has been used to acquire information and to learn about the hazardous environment in Arctic as well as the approach of probabilistic damage stability. It has been motivating to learn and work with subjects that are realistic issues in the maritime industry today and in the future.

I would like to express my deepest thanks to my supervisor Professor Bjørn Egil Asbjørnslett for valuable guidance during the last year. I would also like to thank my co-supervisor assistant Professor Svein Aanond Aanondsen, for help with issues regarding ship design, probabilistic damage stability and with the software DELFTShip. In addition, fellow student Ole Martin Djupvik has assisted me on the subject of probabilistic damage stability and provided me with valuable information. PhD student Martin Bergstöm has provided me with information regarding the risk level of operation in Arctic and documentation on icebergs for use in the thesis. I am grateful for the help and guidance that has been provided during the thesis work. It has been rewarding to get valuable input on the subjects that have been studied during the last year.

Finally, I would like to thank Svein Sollid, the Operation Manager at Hurtigruten AS, for sharing information regarding their vessel MS Fram. It has been much appreciated and helpful to be able to study the arrangement of a vessel that is used for operation in Arctic waters.

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EXECUTIVE SUMMARY

The maritime activity in the Arctic waters has increased during the recent years due to diminishing ice and exploration of resources. Arctic operation involves an increased risk level all year around compared to operation in other open waters. The remoteness of the area and low temperatures can cause severe consequences if an accident would occur due to the possibilities for long waiting time for Search and Rescue (SAR) operations. For the cruise tourism industry the diminishing ice levels entail that more areas become accessible for exploration. The popular cruise tourism areas, around Svalbard, Franz Josef Land and the coast of Greenland are exposed to high concentration of icebergs and succeeding bergy bits and growlers. These smaller ice pieces pose large threats to the vessels operating in the area as they are difficult to detect and can induce large forces on the ship hull in case of impact. In order to ensure the safety of passengers and crew, it is necessary to evaluate measures for improved damage stability. In case of damage of the vessel resulting in water ingress, it is vital that measures have been taken to increase the vessel's capability to remain afloat. By increasing the survivability of the vessel, emergency evacuation can be avoided as the vessel function as ''it's own lifeboat''.

Formal Safety Assessment (FSA) has been performed to assess the risk of cruise ship operation in Arctic, where probabilistic damage stability (PDS) and cost benefit assessment (CBA) is used to evaluate changes in the arrangement for risk reduction. Two risk control options (RCOs) have been developed on the basis of the general arrangement to MS Fram. Risk control option I considers implementation of longitudinal bulkheads in the forward area of the vessel, between the shell and crew cabins located between 1st and 2nd deck. A part of this area is located beneath the waterline, and is therefore exposed for damages caused by impact with drifting ice. Risk control option II considers changes in the arrangement for symmetrical flooding. The tanks located below tank top and below 1st deck are changed from heading in the longitudinal direction to the transverse direction. In case of damages to this area, implementation of RCO II ensures symmetrical flooding to improve the vessel's capability to remain afloat. The two RCOs have been implemented in the software DELFTShip, and compared with the initial arrangement on the basis of the probabilistic damage stability calculations. The increase in the attained index, as a result of the implemented RCOs, is considered as improved capability to remain afloat. The results from the PDS calculations show a slight increase in the attained index for both risk control options. This slight increased index improves the vessel's survivability by increasing the amount of damages where the time to capsize is longer than 30 minutes. The results from the cost benefit assessment show that both RCOs are cost effective and can thus be recommended for implementation.

The analyses are done based on numerous assumptions causing uncertainty regarding the accuracy of the results. However, the results are considered to give an indication on the effect of implementing the measures. Based on the results of the analyses, it is demonstrated that the measures for risk reduction can improve the damage stability of the vessel for cruise ship operation in Arctic

SAMMENDRAG

Den maritime aktiviteten i Arktis har i løpet av de siste årene økt på grunn av det minkende is nivået i området og oppdagelsen av nye ressurser. Skipsoperasjoner i Arktis er utsatt for økt risiko sammenliknet med skipsoperasjoner i andre deler av verden. En grunn er at ventetid på søk og redningsoperasjoner kan ta svært lang tid. Som følge av dette kan en ulykke i området få katastrofale konsekvenser. Cruiseindustrien utnytter at nye områder nå er mulig å utforske på grunn av det minkende isnivået. Svalbard, Franz Josef Land og rundt kysten av Grønland er populære destinasjoner for Arktiske cruiseskip. Disse områdene er utsatt for høy konsentrasjon av isfjell og mindre isblokker som følge av kalving. De mindre isblokkene utgjør en trussel for fartøyene som opererer i området ettersom de er vanskelige å oppdage og vil kunne medføre store krefter på skroget ved et støttilfelle. For å garantere sikkerheten til passasjerer og mannskap er det nødvending å vurdere tiltak for risikoreduksjon ved å forbedre skadestabiliteten. Ved skade på skroget som resulterer i vanninnløp er det nødvendig at tiltak er gjort for øke overlevelsesevnen til skipet. Det vil si skipets evne til å holde seg flytende uten særlig krengevinkel som følge av skaden.

Formell sikkerhetsvurdering (FSA) er utført for å vurdere risikoen av cruiseskipoperasjon i Arktis, der to alternativer for risikokontroll er utviklet for forbedret skadestabilitet på bakgrunn av general arrangementet til MS Fram. Tiltakene er analysert ved hjelp av kalkulasjoner på probabilistisk skadestabilitet og kost-nytte analyse. Alternativ I omhandler å innføre langsgående skott mellom skipshuden og mannskapslugarene i den fremre delen av skipet. Disse lugarene er utsatt for skader påført av is da deler av lugarene er lokalisert under vannlinjen, mellom første og andre dekk. Alternativet for risikokontroll vil dermed redusere sannsynligheten for fylling av vann i mannskapslugarene dersom fartøyet blir skadet av is i den fremre delen av skipet. Alternativ II omhandler endring av tankarrangementet under tanktopp og første dekk fra å gå i langskipsretning til å gå i tverrskipsretning. Denne endringen sørger for symmetrisk fylling dersom dette området skulle bli skadet. Symmetrisk fylling er ønskelig for å unngå krengning, og blir sørget for ved at hele tverrsnittet blir fylt i skadeområdet. De to alternativene for risikokontroll er vurdert ved hjelp av kalkulasjoner på probabilistisk skadestabilitet i programmet DELFTShip. Alternativene er sammenliknet med utgangspunktet og vurdert ved hjelp av den oppnådde indeksen, A. Økning i den oppnådde indeksen er ansett som forbedret flyteevne som følge av skade. Kalkulasjoner på probabilistisk skadestabilitet på de ulike arrangementene viser en liten økning i oppnådd indeks for begge alternativene for risikokontroll. Resultatene fra kost-nytte analysen viser at begge alternativene er vurdert som kostnadseffektive, og tiltakene kan dermed bli anbefalt for realisering.

Analysene som har blitt utført er basert på en mengde antakelser som påvirker påliteligheten til resultatene. Resultatene kan imidlertid bli ansett for å gi en indikasjon på effekten av å innføre tiltakene. Basert på denne antakelsen, har det blitt utviklet tiltak for forbedret skadestabilitet som fører til risikoreduksjon av skipsoperasjon i Arktis.

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LIST OF ACRONYMS

ALARP	As Low As Reasonably Possible
CBA	Cost Benefit Assessment
DDS	Deterministic Damage Stability
DNV GL	Det Norske Veritas Germanischer Lloyd
ETA	Event Tree Analysis
FMECA	Failure Mode Effects Criticality Analysis
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
GA	General Arrangement
GCAF	Gross Cost of Adverting a Fatality
GOALDS	Goal Based Damage Stability
HARDER	Harmonization of Rules and Design Rationale
HAZID	Hazard Identification
HAZOP	Hazard Operability Study
IACS	International Association of Classification Societies
IMO	International Maritime Organization
LMIS	Lloyds Maritime Information Systems
NSR	Northern Sea Route
NSRA	Northern Sea Route Administration
PDF	Probability Density Function
PDS	Probabilistic Damage Stability
PLL	Potential Loss of Life
PHA	Preliminary Hazard Analysis
RCO	Risk Control Option
SAR	Search and Rescue
SOLAS	Safety Of Life At Sea
SWIFT	Structured What-If Technique

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

During the recent years the maritime activity in Arctic waters has increased due to diminishing ice levels and exploration of resources. The sea ice thickness in the Central Arctic Ocean has decreased by 40% over the last 30 years, and model experiments suggest a further decrease of some 30% by 2050 (Østreng et al.).The Arctic shipping activity mainly consists of transportation of cargo, oil and gas related activities and tourism. The cruise tourism industry benefits from the climate change as more areas are becoming accessible for exploration. Arctic cruise activities are primarily made in ice-free waters during the summer season, May to September. However, Arctic operation involves an increased risk level all year around compared to operation in other open waters. The remoteness of the area and low temperatures can cause severe consequences if an accident would occur due to the possibilities for long waiting time for Search and Rescue (SAR) operations.

Cruise vessels with and without ice-class sail in the Arctic waters during the summer months. The vessels operating in the area are exposed to the threats and hazards the area carries. An impact accident with drifting ice can cause major damages to the hull, and in some cases result in flooding of the vessel. In order to ensure the safety of the passengers and crew aboard, it is necessary to evaluate measures for risk reduction. If the increasing interest for the Arctic area continues to grow as it has during the recent years, it will become a necessity to introduce measures to reduce the risk of operation in the area. It is wanted by the industry that the passenger vessels have the ability to function as ‘‘its own lifeboat’’, preventing the need for emergency evacuation. In order to design the vessel with this functionality, it is essential to improve the survivability of the vessel. Survivability is described as the capability to stay afloat after an incident has occurred. In order to increase the survivability of the vessel, measures for improvement of damage stability are fundamental. Damage stability is one of the vital areas of safety legislation since it deals with mitigating the consequences of water ingress in the vessel. Subsequent flooding to internal compartments has led to major casualties on RoPax ships in the past, such as accidents with the vessels MV Herald of Free Enterprise, MV Estonia, MV Jan Eveliusz, MV Express Samina and MV El Salam Bocaccio (Pawłowski, 2004). These accidents prove that damage stability is a highly important factor when considering the safety of ship operation.

Probabilistic damage stability (PDS) is a methodology to find out whether a ship can withstand certain damages in a sufficient manner. The method estimates an individual probability for all possible damage cases a vessel can encounter, multiplied with the probability of surviving the damage based on accidents statistics on ship-ship collisions. The probability and survivability of each damage case is summed up to a final attained index. The attained index is a measure on the safety level of the vessel. The ideology behind the method is that two vessels with the same attained index are regarded as equally safe. By using this approach, the ship designer has more freedom when designing the arrangement, as the design is not bound by the deterministic rules. Probabilistic damage stability enables the possibility to design the vessel in an efficient manner, with the aim of improving the survivability for increased safety level of ship operation.

Use of probabilistic damage stability in risk assessments to evaluate measures for risk reduction has been applied in different studies. The SAFEDOR project was performed to develop a risk-based regulatory framework as well as a risk based design framework. In order to do so, a large share of their work considered a series of application examples of risk-based design to develop new designs that were proven to be as safe as the designs based on the current regulations (Breinholt et al., 2012). As a part of the integrated SAFEDOR project, a risk analysis study on the safety level of RoPax vessels were performed. The study targeted possible improvements on safety levels following large scale flooding by using probabilistic damage stability and cost benefit assessment. The conclusions on the study were that the expected costs associated with the introduction of the measures to improve the survivability in flooded condition, are significantly lower than the willingness to pay for the measures. It was therefor recommended to increase the required subdivision index R for RoPax vessels (Guarin et al., 2009).

There has, however, not been performed any studies on risk reduction for Arctic operation using probabilistic damage stability. The literature review on the subjects relevant for this thesis is a continuous process throughout the report.

1.2 OBJECTIVE

The objective of this master thesis is to evaluate design measures for risk reduction of cruise vessel operation in Arctic, using probabilistic damage stability and risk assessment. Measures for improved damage stability may be developed on the basis of the hazards of operation in the area. The measures may then be evaluated based on the difference in the attained index from probabilistic damage stability calculations. Subsequently recommendations for decision making on the implementation of the measures can be made based on results from a cost benefit assessment.

1.3 SCOPE AND LIMITATIONS

The overall goal for this thesis is to use probabilistic damage stability as a tool in a risk assessment to reduce the risk of operation in Arctic waters by improving the survivability of the vessel.

In sum, this thesis addresses the following:

- Study on the risk related to cruise operation in Arctic waters, including identification of areas with increased risk for hull damages due to ice loads.
- Collection of data on Arctic casualties, iceberg sources and drifting pattern and loads induced on ship hull during impact.
- Foundation and theory for probabilistic damage stability and use of the approach in a risk assessment.
- Development of risk control options based on the weaknesses identified by studying the arrangement of a cruise vessel used for operation in Arctic waters.
- Evaluation of the risk control options for risk reduction using probabilistic damage stability and cost benefit assessment.
- Verification of analysis by evaluating the results and the use of the method on an Artic specific scenario.
- Conclusions and recommendations for further work.

The scope is limited in this context to only consider the hazard contact with drifting ice that causes damages to the ship. The reference vessel used in the analysis is MS Fram, operated by Hurtigruten AS. The vessel is built according to the probabilistic damage stability regulations and operates in Arctic and Antarctica. Simplifications in the arrangement in the modelling of the vessel for the PDS calculations are made based on the information received and details assumed to be insignificant to the purpose of the analysis. The software DELFTShip is used for ship modelling and probabilistic damage stability calculations.

1.4 STRUCTURE OF REPORT

The work in this thesis is performed in three main steps; initial background knowledge relevant for the subjects in the thesis, overview of the theories and methodologies used and a detailed case study on the risk of cruise vessel operation in Arctic, including probabilistic damage stability calculations for the evaluation of risk reducing measures for improved damage stability.

Chapter 2, problem description, gives a thorough explanation of the issues considered in the thesis. Chapter 3 documents the necessary background knowledge, discussing previous studies and data on accident statistics and information regarding drifting ice. Chapter 4 gives an overview of the methods used in the case study, where the analyses are explained in detail in chapter 5. Chapter 6 contains the result from the case study. A thorough discussion of the case study, results and methods used are presented in chapter 7, with final conclusions and recommendations for further work in chapter 8.

CHAPTER 2

PROBLEM DESCRIPTION

The peak of the Arctic cruise season is during the summer months from May to September. Throughout this period the weather conditions are more suitable for exploring with daylight through the whole day and large areas with ice-free waters. Cruise vessels, with and without ice class, sail through the popular tourism areas for exploration. These vessels, especially those without ice class, are exposed to hazards due to the extreme environment throughout the area. Most of these vessels carry from 50 to 500 passengers on their voyages, which necessitates that safety measures are taken to minimize the consequences if an accident would occur. Svalbard, Franz Josef's Land and around the coast of Greenland are areas popular for cruise tourism. These areas are exposed for a high density of drifting icebergs and succeeding calved bergy bits and growlers. These smaller ice pieces are difficult to detect and can induce high loads on the ship hull in case of impact. If the impact scenario results in hull penetration and flooding of one or more compartments, the consequences can be severe. A solution to mitigate the consequences is to use probabilistic damage stability (PDS) to design the watertight arrangement in such a manner that the vessel can sustain the damages. By improving the damage stability of the vessel, the vessels capability to remain afloat after an incident can be improved. This is especially desirable for operation in Arctic waters due to the remoteness of area and possibly long waiting time for search and rescue operations (SAR).

2.1 THE ARCTIC RISK PICTURE

The Arctic area covers 33.4 million square meters and is exposed to seasonal changes more dramatic than any other area in the world. Ship operation in Arctic waters is exposed to a harsh environment and numerous factors that increase the risk level of operation. The risk factors vary depending on type of activity, location and season. DNV GL has developed a tool to map the risk using data from its Arctic projects, where the Safety and Operability index give an understanding of the ever-changing risk levels in the area. The index presents, for instance, that the risk of operation is higher in northwest and northeast of Greenland in the summer than in the Barents Sea during the winter due to the ice conditions around Greenland. The Arctic shipping is anticipated to increase, thus imposing new risks and challenges depending on type of operation, size and design of the vessel, and the experience of its crew. Drifting ice poses a threat to the ship hull and machinery for vessels operating in the area. The harsh climate necessitates that the hull is made of quality materials and that the systems are designed to tolerate the low temperatures. In addition to the unique risks that the ships are exposed to in the Arctic, the ships face many of the same hazards met by ships operating all over the world. The risk of collision, however, is lower due to less ship traffic. The main risk factors a ship are exposed to when operation in the Arctic waters are listed in table 1. The risk factors are based on DNV-GL research and experience from projects in the area (DNV-GL, 2014)

Table 1: Risk factors in Arctic (DNV-GL, 2014)

Operational	Environmental	Infrastructure	Human Related
Traffic density	Current	Emergency and evacuation capabilities	Local experience
Convoy	Wind	Navigational aids	Cold operation competence
	Waves		Ice navigation competence
	Visibility due to snow or fog		Crew fatigue
	Daylight		
	Water and air temperature		
	Marine and atmospheric icing		
	Drifting ice (icebergs, bergy bits, growlers, large floes)		

As seen from the risk factors in table 1, there are many environmental factors that influence the risk of operation. The main factor that influences the damage stability is drifting ice, as impact can induce high loads on the ship hull. This is considered a likely scenario for Arctic cruise operation that takes place near Svalbard and around the coast of Greenland. These areas are exposed to drifts with icebergs, bergy bits and growlers. Icebergs are often easily detected by radars and sight. Bergy bits and growlers can on the other hand be difficult to detect, as the ice pieces have a length below 20 m, and height above the water surface below 5 m. If the drifting ice pieces are not detected, and thus the vessels sails towards the drift without reducing the vessel speed, an impact can lead to large impacts loads causing hull penetration and succeeding water ingress.

2.2 PDS BASED ON SHIP-SHIP COLLISION

Probabilistic damage stability is based on accidents statistics on ship-ship collisions. The accident categories are all related to the ship's damage stability, as the consequence of an accident could be that water enters into the ship. The following events are dependent on the vessel's capability to remain afloat in an acceptable condition. There have been various research projects for the development of better regulations regarding PDS, such as Harmonization of Rules and Design Rationale (HARDER) and Goal Based Damage Stability (GOALDS). The HARDER project collected casualty data to develop damage statistics on ship collisions. The collected data consisted of more than 2900 casualties collected from various sources, and the project developed proposals on the probabilistic regulations based on test calculations on a sample of 40 passenger ships and 92 dry cargo ships. The objective of the project was to harmonize the damage stability regulations for all vessel types by using the probabilistic damage stability concept (Olufsen and Hjort, 2013).

The probabilistic damage stability method uses the probabilities for the location of damage, damage extent and survivability for calculations on each possible damage the vessel can suffer. As the probability distributions are developed based on damages caused by ship-ship collisions, the PDS calculations on a scenario that considers impact with ice will be affected.

2.3 PDS FOR ARCTIC OPERATIONS

Probabilistic damage stability is developed based on accident statistics from all areas. Damages that occur in Arctic areas are often related to damages from ice loads. These statistics are not considered in the development of the probabilistic damage stability rules, affecting the results of using the approach for Arctic specific accident scenarios. The methodology considers damages that have a damage extent above the waterline. In order for the method to be relevant for an impact scenario with drifting ice, a part of the damage extent must cover an area above the waterline. The ice pieces must therefore be of such a size that it causes damages above the water surface. Bergy bits and growlers have their largest area beneath the water surface, thus damage due to impact will likely cover an area below the waterline as well. When evaluating options for risk reduction for ship operation in Arctic, the measures should focus on the forward part of the vessel, from the baseline to the decks located up to 5 meter above the waterline. This area is highly exposed for damages from drifting ice pieces.

Since the statistics used to develop the probabilistic damage stability regulations does not consider casualties due to ice loads, the use of the method for the Arctic specific accident scenario will not give completely reliable results. As the measures that will be considered in this thesis will be developed based on damages from ice loads, the real effect of implementation can possibly be considered to be even greater than what the results will show. Two factors will likely cause a deviation when using the method for the Arctic specific accidents. The first factor is related to that the probability of experiencing damages in the forward part of the vessel can be considered to be greater when operating in an area with high density of drifting ice than in open waters. In a ship-ship collision scenario, the striking ship is often damaged in the forward part of the vessel, as it is usually headed in the forward direction, but the struck vessel has a likelihood of suffering damages over the entire ship length. The frequency of damages located in the forward area can therefore be assumed to be larger when operating in Arctic areas, due to the high exposure of drifting ice. The other factor is that the damage extent will differ from the damages in the database, as the damage extent caused by ice pieces, in the bergy bit and growler size, will likely cover a smaller area with a lesser penetration extent than the damages from the damage statistics.

However, it is assumed that the use of the method can give an indication of the effect of introducing the risk-reducing measures to the vessel design. On the basis of these assumptions, using probabilistic damage stability for improved damage stability for ship operation in Arctic is considered to give somewhat reasonable results.

CHAPTER 3

BACKGROUND INFORMATION

Chapter 3 is meant to provide the necessary background information to use in the case study in chapter 5.

3.1 RISK ACCEPTANCE CRITERIA

Risk acceptance criteria are the limits for acceptable risk to be used in the analysis in the thesis. The risk acceptance criteria for individual and societal risk to be used are as proposed in MSC/72. Individual risk is expressed as the frequency of an individual fatality per year and is at the same level as those published by the UK Health and Safety Executive (IMO, 2000). The individual risk acceptance criteria are listed in table 2.

Table 2: Individual risk acceptance criteria (IMO, 2000)

Boundary between negligible risk and ALARP area	Maximum tolerable risk for passengers	Maximum tolerable risk for crew
10^{-6} per year	10^{-4} per year	10^{-3} per year

As this thesis addresses safety measures for passenger vessels the main concern is the societal risk criteria, since an incident can in worst-case result in loss of life of a large number of people. The societal risk criteria are based on data from 1989 to 1998 in Lloyds Maritime Information Systems (LMIS) casualty database. Societal risk criteria is presented in FN curves that present the annual frequency of occurrence of N or more fatalities. The FN curve in figure 1 is in logarithmic scale and shows the number of fatalities on the x-axis, and the frequency of the fatalities on the y-axis. The line in the figure is a representation on the calculated societal risk evaluation criteria for passenger Ro/Ro vessels (Papanikolaou, 2009). The limits for the as low as reasonably possible (ALARP) area is clearly represented in the diagram in figure 1. When the activity involves over a hundred people, the limit for intolerable risk it at a frequency of occurrence of approximately 10^{-3} per ship year. The risk level is never in the negligible region when the activity involves hundred people or more. When the risk is in the ALARP area, risk control options should be considered for implementation if the options are calculated to be cost effective, while in the intolerable area measures must be taken to reduce the risk. When an activity involves a thousand people, the risk level is considered to be intolerable in the frequency level 10^{-4} per ship year. The vessels operating in the Arctic waters have a typical capacity of up to 500 passengers, thus the risk should always be reduced if it is regarded as cost effective.

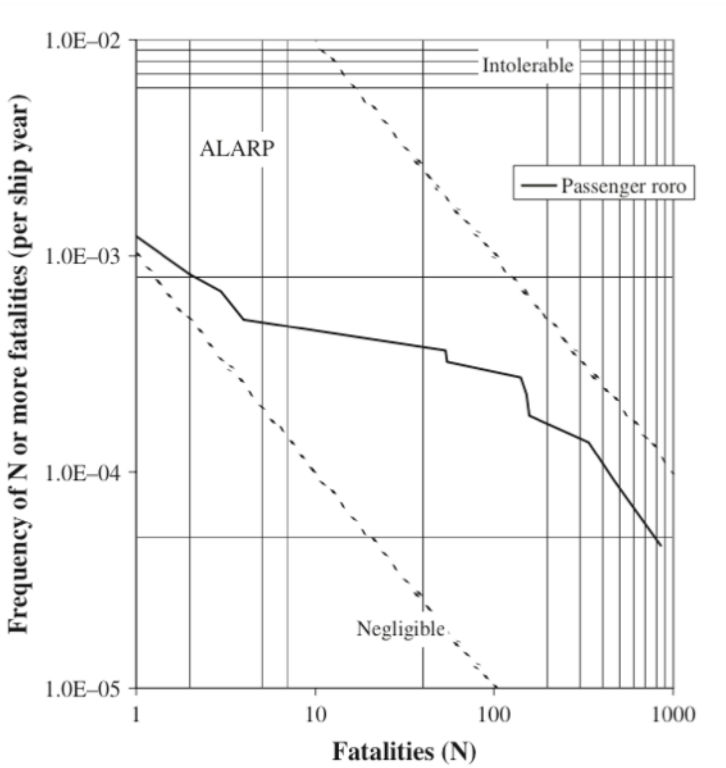

Figure 1: FN curve societal risk criteria (Papanikolaou, 2009)

3.2 ACCIDENTS STATISTICS

According to the latest Safety and Shipping Review there has been an increase in maritime accidents in the Arctic area as a result of the increased activity during the recent years. In 2014, there were 55 shipping casualties in Arctic, compared to only 3 a decade ago. Between 2005 and 2014, there were reported 31 total losses in the Russian Arctic and Bering Sea, and 14 total losses in the Canadian Arctic and Alaska. Figure 2 shows a table of all casualties, including total losses, from 2005 to 2014.

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Machinery damage/failure	2	3	5	13	14	16	12	13	20	27	**125**
Wrecked/stranded	1	4	10	11	14	9	9	8	10	14	**90**
Miscellaneous			5	1	4	4	2	6	5	5	**32**
Fire/explosion			3	1	2	6	6	1	4	2	**25**
Collision				1	4	10	4	4	2		**25**
Contact (eg harbor wall)			1	1	1	3	1	3	6	4	**20**
Hull damage		1	3	1	6	2	2	1	2	1	**19**
Foundered			1	1	2		3	1	1	2	**11**
Total	**3**	**8**	**28**	**30**	**47**	**50**	**39**	**37**	**50**	**55**	**347**

Figure 2: Accident statistics in Arctic (Allianz, 2015)

As seen in figure 2, machinery damage/failure is the principal cause to the casualties, causing 36 % of the incidents. 9 % of the casualties are due to hull damages and 6 % due to contact. The accident statistics does not state how many of the contact casualties that are caused by contact ice, but implies that several of the casualties are related to contact with the harbour wall (Allianz, 2015). A database on ship collisions with icebergs concentrated on the North Atlantic area off Newfoundland and the area around Greenland has been done investigating incidents from 1686 to 2000. The database includes incidents with bergy bits and growlers, counting 12 impacts with growlers and 6 impacts with bergy bits. These numbers give a combined frequency of impact of 0,05732 each year (Hill, 2010). A large part of the casualties listed in the database occurred several years ago and contain little to no information regarding the casualties. It can be presumed that many incidents have occurred during these years that have not been reported, making the database incomplete.

In order to give an impression of the accident scenarios that are considered in this report, two accidents occurred in the Arctic are briefly explained. In September 2013, the 138 m long tanker *Nordvik* was struck by an ice floe and suffered water ingress in one of the ballast tanks when sailing in the Kara Sea. The vessel, which was loaded with diesel, is an Ice 1 class tanker and was permitted to sail in the Northern Sea Route (NSR) in light ice conditions. The conditions were regarded as medium in the period of the accident. The Federal Agency for Sea and River Transport reported that *Nordvik* acted irresponsibly when entering the waters with medium ice conditions without having assistance of an icebreaker. On the other hand, experienced captains stated that it was possible to unintentionally end up in an area with medium ice conditions, as the conditions could change rapidly. The accident revealed that ship owners does not always comply with the flag state rules, in this case Northern Sea Route Administration (NSRA), when operating in their jurisdiction. In June 1989, the cruise ship *Maxim Gorkiy* was hit by an ice floe in the Greenland Sea, near Spitsbergen. The vessel began to sink quickly causing the passengers and crew to evacuate. A part of the crew stayed in the vessel in effort to stop the flooding. The crew managed to save the vessel from sinking and *Maxim Gorkiy* was later towed to Svalbard. The accident report states that the reason for the accident was that the Master decided to pass the ice field without lowering the ship speed as he considered the conditions to be lighter than it actually was (Marchenko, 2014). Both of the accidents mentioned are caused due to underestimation of the ice conditions. Fortunately, the accidents occurred without any loss of life or significant oil spill. These accidents demonstrate that even though the vessels are designed to operate in light ice conditions, an impact casualty with drifting ice can result in severe damages to the hull. Both of the incidents are reported as impact with an ice floe. It can be difficult to differentiate a large ice floe from a bergy bit, thus it is possible that it was glacier ice that caused the damage in the two casualties. The accidents revised and accidents statistics on maritime casualties show that human error is responsible for most of the marine accidents. This demonstrates that measures must be considered to ensure the safety of passengers and crew that are not dependent on the human performance (Itoh et al., 2001)

3.3 DATA ON ICEBERG, BERGY BITS AND GROWLERS

Icebergs differ from sea ice as they are formed from freshwater-ice originated on land. The Canadian Coastguard defines a bergy bit as a piece of glacier ice showing from 1 m to 5 m above sea level, with a length between 5 m and 20 m. Growlers are smaller pieces of glacier ice showing less than 1 m above sea level, with a length of less than 5 m. The growlers are often transparent and appear almost green or black on the water surface, making them difficult to detect. Icebergs are glacier ice pieces larger than bergy bits, where the bergy bits and growlers are formed by calving from the icebergs (Canadian Coast Guard, 2013). The smaller ice pieces in the bergy bits and growler range can generate large forces upon impact with structures, it is therefore valuable to have information about the probability of encountering these small pieces drifting near the parent iceberg. Depending on the relative velocities between the parent iceberg and smaller ice pieces, there is a maximum distance that the smaller ice piece travel before they melt to a negligible size, i.e. that will not cause damage in case of impact. Several studies have collected data on iceberg sizes and distributions, but most of them are focused on the parent iceberg. Few studies include accurate information on smaller pieces, in the bergy bit and growler size range. This is partly because of the difficulties in making measurements of the smaller pieces, the large number of pieces generated from the calving and the earlier lack of concern regarding the smaller pieces. However, two studies have been done on the collection of data on small pieces calved from icebergs. A collection of data from the inner 10 km of Kongsfjorden, located on the northwest of Spitsbergen (Dowdeswell and Forsberg, 1992), and a collection of data from Bonavista Bay in Newfoundland (Crocker, 1993). The results from the latter of the two studies are described in the following sub-chapters.

The origin of a drifting iceberg can be predicted by means of ice temperature measurements as the temperature of the parent glacier is preserved in the interior of the iceberg. Franz Josef Land is the largest source of glacier ice in the Barents Sea. This archipelago is made up of 40 islands where most of them are ice-capped. Several of the islands are surrounded by deep water so there are large areas of floating ice shelves and thus a high production of icebergs (Løset, 1993b, Løset, 1993a). An additional large source for icebergs is the Greenland ice sheet. Tens of thousands of icebergs originate from Greenland Glaciers each year, where a large portion of the icebergs drift south towards the Grand Banks (Ebbesmeyer et al., 1980).

3.3.1 Drifting pattern and density/frequency

Normally, when calving occurs, the calved ice breaks into thousands of pieces in a large size variety, where the smaller pieces represent the largest amount. In Crocker's study mentioned above, he concluded that per calving event 13,9 particles between 5 and 20 m are produced. Of these 13,9 particles, only 1,9 have a length above 10 m. The size distributions of the calved ice particles were gathered using aerial photographs. Several aerial surveys were performed and a total of nine different icebergs were photographed, where 3461 ice particles were documented (Crocker, 1993). Figure 3 show the average number of particles calved between 5 and 20 m per calving event as a function of length, while figure 4 show the average number of particles calved per calving event as a function of mass.

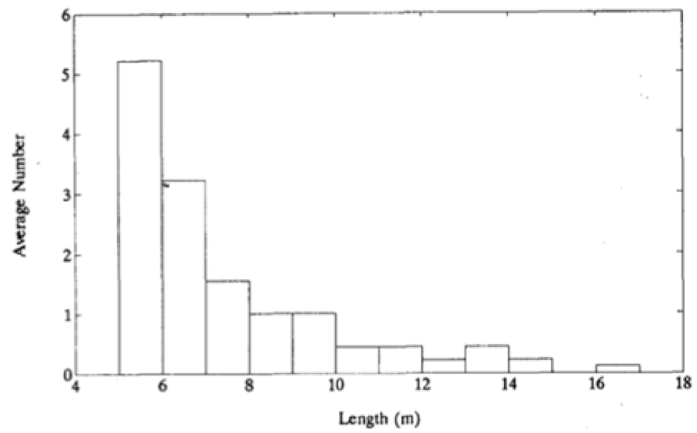

Figure 3: Average number of particles as a function of length (Crocker, 1993)

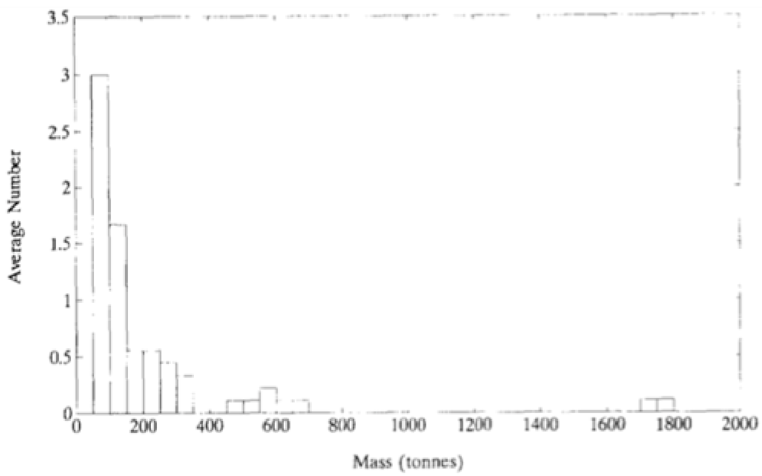

Figure 4: Average number of particles as a function of mass (Crocker, 1993)

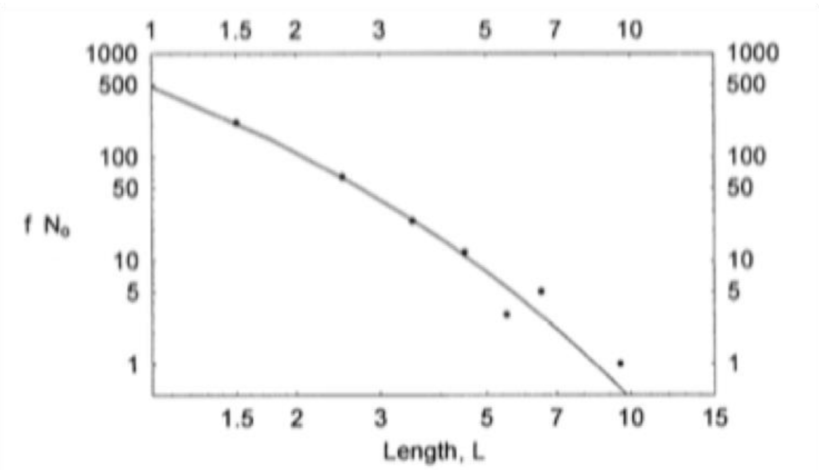

Figure 5: Size distribution of calved piece (Savage et al., 2000)

Based on the same data, a study was performed to develop size-frequency distribution functions. In figure 5, N_0 is the total number of ice pieces, f (L) is the normalized size-distribution function and L is the length of the ice pieces. The size-frequency distributions were compared to the curve fits corresponding to the data sets from the previous studies (Savage et al., 2000). It is assumed that the general form of distribution will be the same in other regions. Based on this information, mapping of iceberg data can be used to estimate a probability of encountering bergy bits and growlers depending on the calving frequency.

The Greenland ice sheet, Franz Josef Land archipelago and Svalbard archipelago are the main iceberg sources affecting cruise shipping in Arctic waters. A study on iceberg drifting in the Barents and Kara Sea were conducted from 1987 to 2005, where Svalbard, Franz Josef Land and Novaya Zemlya were the main sources for icebergs in the area. Based on the calving rate and mean size of icebergs, estimations were made on average number of icebergs released each day from the different sources. Given that the estimations are accurate, the annual number of icebergs calved each year would be 19,000 to 20,000. Based on the study, around 77% of the calved icebergs each year become grounded, where the average iceberg spend approximately 42% of their lifetime motionless. 20% of the icebergs survive more than one year and merely 3.3% survives more than two years. A map illustrating the probability of encountering an iceberg during one year demonstrates that most of the icebergs are located close to the calving sources. The probability of encountering an iceberg is highest near the source and gradually decreases with the distance from calving (Keghouche et al., 2010).

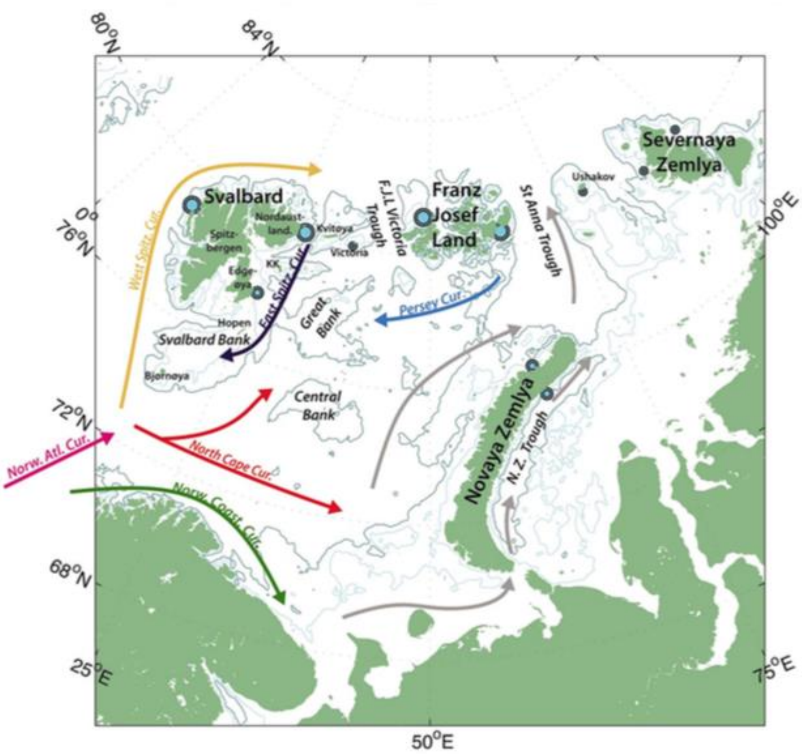

Figure 6: Iceberg sources, Svalbard and Franz Josef Land (Keghouche et al., 2010)

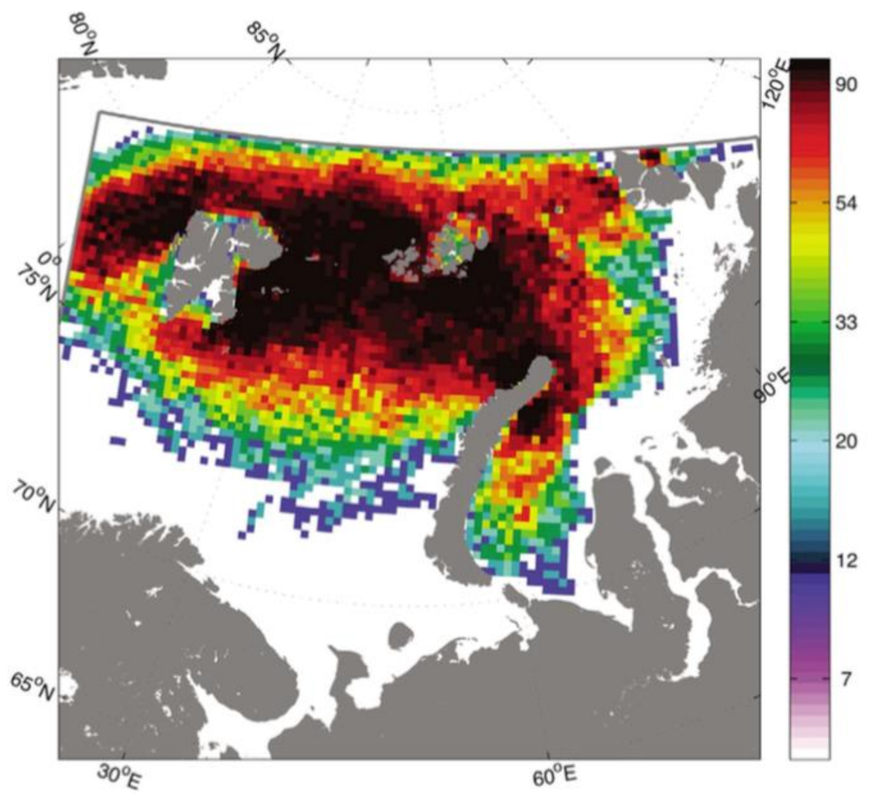

Figure 7: Probability of encountering an iceberg (Keghouche et al., 2010)

Figure 6 illustrates the different sources of icebergs (blue circles) and the ocean currents where the icebergs drift. Figure 7 shows the probability of encountering an iceberg within a year. The map presents high probabilities (red and black) of encountering icebergs around Svalbard to Franz Josef Land. These areas are popular routes for cruise tourism.

There are mainly two different calving processes from icebergs. The first process is wave erosion of material at the waterline. Waves can cut rounded notches in the iceberg where the water velocities are largest. When the notches become deeper, an overhang above the waterline develops causing bending stresses due to the weight of the overhang. Eventually the bending stresses will become so great that the ice fractures and the piece fall off. The second calving process is due to stresses caused by buoyant forces and or grounding. Similar calving can occur due to thermal stresses caused by solar radiation or rolling in warm waters. The size distributions of ice pieces are relatively similar for the different processes (Crocker, 1993).

Based on the studies on icebergs, bergy bits and growlers mentioned, there are large probabilities of encountering areas with high density of bergy bits and growlers calved from icebergs when sailing in the popular cruise routes. Icebergs are usually easily detected on the ship radar, while objects in the growler and bergy bits size range can be difficult to detect. In order for the vessel to avoid contact with the drifting ice if it is on the vessel's course, it is dependent on identifying the ice piece.

3.3.2 Impact load

A study on bergy bit impact using an impact panel to measure force and pressure during contact between a ship and ice pieces has been performed. The impact scenarios considered a vessel that was struck by bergy bits and a small iceberg over a range of ship speeds, between 5 and 12 knots. The bergy bits used in the analysis varied in size between 100 to 22,000 tonnes. The analysis was performed using a novel external impact panel, mounted on the ship hull. Figure 8 show the size and mass of different bergy bits used in the study, while figure 9 show a plot of the peak impact load versus ship speed (Gagnon, 2008).

Berg ID	Shape	Dimensions			Mass (tonnes)
		Length (m)	Width (m)	Height (m)	
04	Dome	7	–	–	114
05	Wedge	73.5	23.6	12.9	22045
06	Dome	8	–	–	171
09	Dome	9	–	–	243
11	Dome	14	–	–	915
12	Dome	11.3	–	1.8	671
14	Dome	16.6	11.3	3.1	1911
16	Dome	18.4	14.2	4.3	2838

Figure 8: Mass and size of bergy bits (Gagnon, 2008)

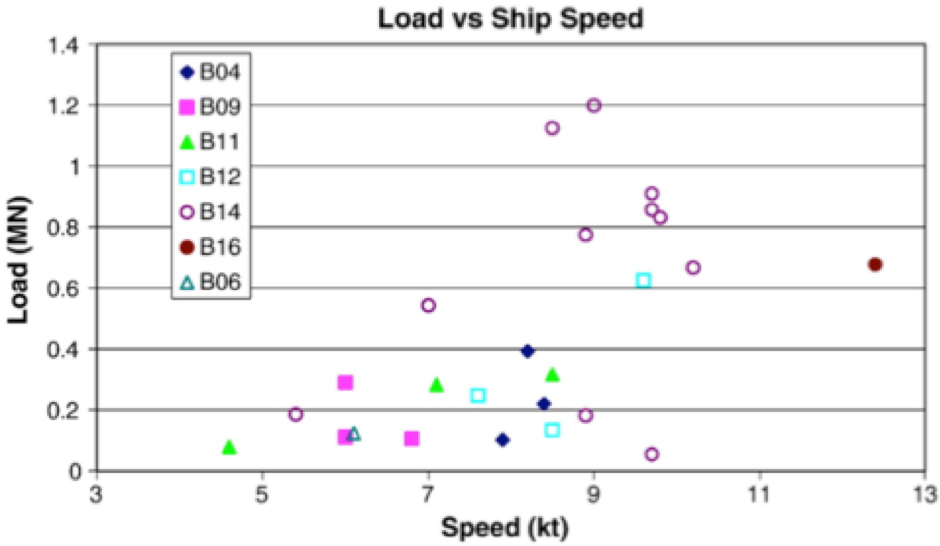

Figure 9: Impact load vs. ship speed (Gagnon, 2008)

The study demonstrates that the small pieces can result in an impact load up to 1.2 MN with a vessel speed of just 9 knots. Cruise vessel sailing speed is often higher than this causing the impact load to be even higher. The impact that resulted in the highest impact load was with an ice piece mass of approximately 1900 tonnes and length of 16 m.

3.4 TRAFFIC MODEL

The traffic model in figure 10 illustrates a calving event of an iceberg where bergy bits and growlers are formed. The iceberg, bergy bits and growlers will follow the current, where it may be assumed that the two latter groups will drift with a higher velocity than the parent iceberg due to the smaller mass. This assumption is dependent on the wind and current where the smaller pieces are more influenced by the wind than the iceberg, which is moving along with the current. In addition to the bergy bits and growlers, several smaller ice pieces will form from the calving. The ice pieces that are smaller than the growler range are not considered to pose a threat to the approaching vessel. The vessel is headed towards the current with drifting ice pieces. When sailing through the current, the vessel is in a hazardous situation as there is a high likelihood of bergy bits and growlers in close proximity. The crew on board the vessel is in suspense of the hazardous situation if the ice pieces are not detected, and the vessel continues without decreasing the sailing speed, as an impact scenario can have severe consequences. The illustration is made to give an impression of the impact scenario, thus the sizes of the different objects in the drawing can deviate in a virtual scenario.

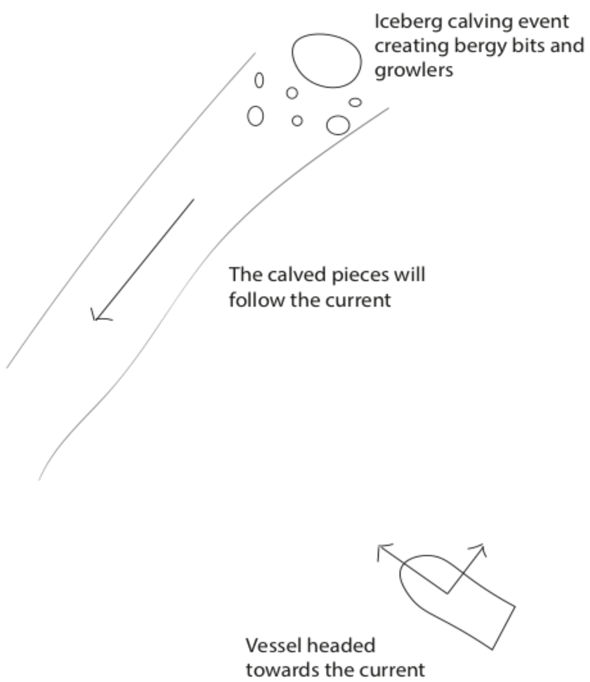

Figure 10: Traffic model

3.5 CONCLUSIONS ON THE BACKGROUND STUDY

Statistics on casualties in the Arctic Circle during the recent years show an increase in the frequency of casualties as the maritime activity in the area increases. There have been reported 20 contact casualties in the area during the last 10 years. Based on the information gathered in this chapter, it is demonstrated that the popular cruise tourism areas around Svalbard, Franz Josef Land and the coast of Greenland are high-risk areas for exposure of icebergs. As the cruise vessels operating in Arctic areas usually have a passenger capacity of around 500 people, the societal risk limit for intolerable risk is at 10^{-4} per ship year. The areas mentioned are sources for icebergs and succeeding growlers and bergy bits. Calving from icebergs occurs periodically and per calving event of a large iceberg, 13,9 particles between 5 and 20 m are produced. These pieces pose large threats to the ships operating nearby. Studies on bergy bits and growlers show that an impact with ice pieces in a various range of ship speeds, result in high impact loads on the vessel. As the ice pieces in the growler and bergy bit size range can be difficult to detect, these small ice pieces can cause extensive damages to the vessel if the vessel speed is not reduced. Normal sailing speed for cruise vessels with a capacity of 500 passengers sail with a speed around 13 knots.

Based on this information, an impact scenario with a bergy bit or growler can result in penetration of the shell and succeeding water ingress, dependent on the size of the ice piece and vessel speed. The ice pieces can be difficult to detect, increasing the likelihood of an impact scenario in high speed.

CHAPTER 4

THEORY AND METHODS

4.1 RISK BASED SHIP DESIGN

Risk-based design is a methodology with the objective to maximize safety in the design. In the maritime industry rules are usually only changed or altered after an accident has occurred, thus by implementing a risk-based design methodology, it is more likely that accidents can be prevented. The maritime transport industry is expected to grow, causing a need for innovative and sustainable ships and shipping concepts. Risk-based design makes it possible to implement innovative solutions that cannot be approved today due to limitations in the current rules and regulations.

The basis for all ship design is the international rules and regulations in force when the ship is constructed. The standard ship design process is somewhat straightforward, using previous experience and knowledge from the shipyard and the designer. Sometimes the ship owner wants solutions that challenge the current regulations such as ship parameters, new type of operation, innovations in design and needs due to operations in new areas and so on. In this situation the risks of the new concept must be assessed, and the approval authorities must be involved to approve the new designs. The requirement is that new designs must be as least as safe as the conventional design, i.e. solutions that are designed by following the rules. The trend in the industry is going towards more use of a risk-based approach, deterministic to probabilistic.

Probabilistic damage stability can be used to quantify the risk level and improve the design using a risk-based approach, where the risk level of the design and design improvements should be assessed. The following sub-chapters cover the methodology for risk assessment and probabilistic damage stability, and an explanation on how the two methodologies can be combined for the evaluation of measures for risk reduction.

4.2 RISK ASSESSMENT

Risk is a term with many different definitions, and there is still no commonly agreed definition of the word. ''What is the risk?'' usually covers the three questions: what can go wrong, what is the likelihood of that happening and what are the consequences (Rausand, 2011)?

In this thesis, the words and definitions used for risk management are as proposed in ISO 31000. A risk assessment is the overall process of risk identification, risk analysis and risk evaluation. Risk assessments contain numerous words and definitions to explain the different scenarios. The definitions are important to understand in order to follow the progress of a risk assessment. The terms and definitions often used in risk assessment are explained in the following. Risk identification is the identification of risk sources or hazards, events and their potential consequences. A risk source is defined as an element, which alone or in combination has the intrinsic potential to give rise to risk, while a hazard is defined as a source of danger that may cause harm to an asset. A hazardous event is the first event in a sequence of events that, if not controlled, will lead to undesired consequences. A consequence is the outcome of the event, and likelihood is the chance of something happening. In the work that will be performed in this thesis, risk is measured in terms of likelihood of an event and the consequences as result of the event occurring (ISO31000, 2009, Rausand, 2011).

4.2.1 Formal Safety Assessment (FSA)

Formal Safety Assessment (FSA), developed by the International Maritime Organization (IMO), is a method to assess the risk and evaluate mitigating measures for a system. The method was developed as response to the Piper Alpha accident in 1988 where 167 lives were lost. FSA is now being used in the IMO rule making process and consists of five interrelated steps (IMO, 2002):

1. Identification of hazards
2. Assessment of the risk arising from the hazards identified
3. Identification of risk control options
4. Cost benefit assessment of the risk control options
5. Recommendations for decision making

Step 1 comprises the use of creative and analytical techniques for identification of relevant hazards. The identified hazards and associated scenarios should then be ranked in order to get an overview of the hazards that should be prioritized and disregarded. The ranking is carried out using available data and expert judgement. The purpose of step 2 is to perform a detailed investigation of the causes and consequences of the scenarios identified in step 1. Factors that influence the level of risk should also be identified. Fault trees and event trees are standard techniques for development of a risk model. Data on accidents and failures are used for quantification. In cases where data is unavailable, calculation, simulation and expert judgement can be used. The output from the risk analysis is identification of high-risk areas that need to be considered. The purpose of step 3 is to propose effective risk control options (RCOs). The RCOs are evaluated by implementing the measures in step 2 to see the resulting risk reduction effectiveness. Step 4 comprises of comparing the benefits and costs associated with implementing the different RCOs identified in step 3. The RCOs should be ranked from a cost benefit perspective to facilitate the decision-making recommendations in step 5. Costs should include life cycle cost including costs related to initial, operating, training, inspection, certification, decommissioning costs etc. Benefits should include reductions in fatalities, injuries, environmental damage and clean-up, protection of third party liabilities and increase in average ship lifetime. The purpose of step 5 is to outline recommendations to relevant decision-makers based on the results from step 1 to 4 (IMO, 2002).

The FSA process can be considered as a way of ensuring that action is taken before a disaster occurs. The method enables the combination of the various technical and operational issues with the human element, where safety and costs are the main focus. Application of FSA is principally relevant for the evaluation of proposals on regulatory measures in the maritime industry. Only a few FSA studies performed in the industry has led to IMO decisions. A FSA study was performed on the bulk carrier safety related to the fore-end watertight integrity. The study was carried out by the International Association of Classification Societies (IACS) with the objective to mitigate the risk of fore-end flooding. The study concluded with, among other issues, that double skins were regarded as cost effective, and should thus be implemented. This adoption was later dropped by IMO. A FSA study on cruise vessel navigation was conducted with the objective to mitigate the risk of collisions and groundings. The study concluded with a number of risk control options related to the navigation that was considered cost effective (Papanikolaou, 2009).

Methods and tools that are used in a FSA process are briefly described in the following chapters.

4.2.2 Hazard Identification (HAZID)

The objective of hazard identification is to identify all relevant hazards and hazardous events during all use, intended and misuse, of a system, including the interactions with other systems. Hazard identification is often done by using brainstorming techniques to answer the question ‘‘what can go wrong?’’ When all the relevant hazards are identified, it is necessary to describe the characteristics, form and quantity of each hazard. When and where the hazards are present and possible triggering events must be distinguished. In addition to the brainstorming technique often used, there are several methods for hazard identification such as preliminary hazards analysis (PHA), failure mode effects and criticality analysis (FMECA), hazard operability study (HAZOP) and structured what-if technique (SWIFT). The methods differ in practice, but all have the same objective to identify the relevant hazards for the system under consideration. No method can identify all the hazardous events that can potentially take place in a system, as it is always possible that unidentified hazardous events will occur. The quality and effectiveness of a hazard identification analysis is highly dependent on the experience and creativity of the team performing the analysis (Rausand, 2011).

4.2.3 Fault Tree Analysis (FTA)

Fault tree analysis (FTA) is a logic diagram illustrating the causal relationship between events, which individually or combined cause the occurrence of a hazardous event. The development of FTA diagrams is by a top-down approach, considering the causes or events at the levels below the top level. In scenarios where two or more lower events need to occur to cause the next higher event, this is illustrated by a ''and'' gate. In scenarios where one of two or more lower events can cause the next higher event, this is illustrated by a ''or'' gate. The analysis considers common cause failures in systems with redundant or standby elements and failure events, or causes related to human factors (IMO, 2002).

4.2.4 Event Tree Analysis (ETA)

Event tree analysis (ETA) is a logic diagram for the analysis of the effect of an accident, a failure or an unintended event. The diagram illustrates the probability or frequency of the accident linked to the barriers to mitigate or prevent escalation. The probabilities of the success or failures of these barriers are analysed and lead to various consequences of different severity or magnitude. By multiplying the likelihood of the hazardous event with the probabilities of failure, or success of the different barriers, gives the likelihood of each consequence (IMO, 2002).

4.2.5 Cost Benefit Assessment (CBA)

Cost benefit assessment (CBA) is a method to evaluate the benefit of a risk control option. If the risk level of a system is in the ALARP region, the risk reducing measure should be implemented if the cost of the measure is not grossly disproportionate to the benefit gained by implementing it. In other words, the measure should be implemented if it is cost effective when considering both costs and risk reduction. If a high-cost measure gives little risk reduction, the measure is usually not considered cost effective. A disproportion factor d may be calculated using equation 1, in order to establish a requirement to be used to verify the benefit (Rausand, 2011).

$$d = \frac{cost\ of\ the\ risk\ reducing\ measure}{benefit\ of\ the\ risk\ reduction} \qquad Eq. 1$$

The cost of implementing the risk control option is an approximation of the total cost, including the purchase, installation and training cost, as well as the cost related to the implications of implementing the measure. Such implications can be reduced productivity or reduction of space, where the latter is considered highly undesirable in a ship designer's perspective. The benefit of implementing a risk reduction measure is the ''cost reduction'' related to fewer casualties as consequence of implementing it. The estimation of disproportionality is done by defining a limit for disproportionality d_0. If the calculated factor is less than the limit, the measure should be implemented. The disproportionality limit defines that for a measure to be rejected, how many more times larger the cost should be than the benefits from implementation. A challenge with the cost benefit method is difficulties with expressing costs and values for human life. An alternative is to calculate the cost benefit ratio for any risk reducing measure and look for any unreasonable situations by using reason and previous experience.

Modern risk assessments express their results in the form of Gross Cost of Averting a Fatality (GCAF) to evaluate if the risk option is to be adopted or not. GCAF is calculated using the formula in equation 2.

$$GCAF = \frac{\Delta Cost}{\Delta Risk} \qquad Eq. 2$$

Where $\Delta Cost$ is the marginal (additional) cost of the risk control option and $\Delta Risk$ is the reduced risk in terms of fatalities averted. A study done in 1995 presents the average values of willingness to pay in actual decisions. In Norway the GCAF for all hazards were 10 million NOK for averting a fatality. The net present value in 2014 is 14,5 million NOK, thus a value of 1,93 million USD. In other words, if the GCAF of the risk control option is larger than 1,93 million USD, the option should not be implemented by using the willingness to pay value (Papanikolaou, 2009).

Potential loss of life (PLL) is an expression for the annual fatality rate related to the accident scenario under consideration. PLL can be calculated using equation 3.

$$PLL = \sum_n \sum_j (f_{nj} \cdot c_{nj}) \qquad Eq. 3$$

Where f_{nj} is the annual frequency of accident scenario n and personnel consequence j. c_{nj} is the expected number of fatalities for accident scenario n with personnel consequence j.

The risk benefit is often set to the reduction in potential loss of life as a result of implementing the measure in equation 2.

4.2.6 Risk Evaluation and Acceptance Criteria

In order to perform a risk assessment it is necessary to define an acceptable risk level, both individual and societal, as an acceptable loss of life. The acceptable risk level is specified in risk evaluation criteria, often expressed as 'risk acceptance criteria'. In shipping however, IMO uses the term risk evaluation to indicate that the criteria will not be used as the only decision criteria. There are many methods for establishing risk acceptance criteria, and there are continuous discussions on the subject. It is, and will continue to be, difficult to set a limit for acceptable risk as the criteria also sets a value for an acceptable loss of life. The main methods for defining the criteria is to compare with other hazards, natural hazards and risks people normally take. Comparing with hazards involves relating the criteria with other industries that is considered to be a reasonable target, and where documentation is sufficient. Comparing with natural hazards relates to comparing the things we do ourselves with things the nature does to us. Risk related to human activity should be smaller than risk posed by nature. Comparing with hazards we normally take is associated with that people do a number of hazardous things that we do not consider dangerous in our daily life, such as crossing the street, driving cars and etc. In addition to these comparisons, the level of acceptable risk should be compared with previous decisions made in democratic forums, such as risk assessments done by different national organizations and later made public.

''As low as reasonably possible'' (ALARP) is a principle used in establishing risk criteria. The principle states that money should be spent to reduce risk until the risk level is reasonably low. In other words, money should be spent as long as it is cost effective to do so and the risk is not negligible. In cases where a tolerable level of risk can be reduced further with a reasonable cost, the measure should be implemented. Risk is divided into three levels when using the ALARP principle, an intolerable region, ALARP region and a broadly acceptable region. Risk reducing measures are mandatory in the intolerable region while no further risk reducing measures are needed in the broadly acceptable region. Upper and lower limits for the ALARP region, relevant for the operational context, must be decided for application of the risk acceptance principle.

Risk acceptance criteria can be expressed either implicit or explicit. In a risk analysis the acceptance criteria should be given explicit in order to determine if the risk level is acceptable or not. The criterion is divided into individual, societal and environmental risk. The individual risk criteria are related to what is an acceptable loss when considering activities where few people are involved. In a maritime setting, the objective of individual risk evaluation criteria is to limit the risk to people on board the ship or individuals that may be affected by the activity. In modern risk assessments, individual risk criteria that define limits for intolerable and broadly acceptable risk are used.

The societal acceptance criteria are related to what is an acceptable loss of life when considering activities where groups of people are involved. The criterion is strict, as loss of life of a large number of people is considered highly unacceptable in modern society. The societal risk criterion is usually represented in FN diagrams. The FN curve presents the consequences, in number of fatalities and frequencies per year. In addition to fulfilling the requirements of acceptable risk level, individual and societal, the activity must also comply with an acceptable environmental risk level. Activities that pose a risk for the environment and animal life by pollution, such as emissions and oil spill, must be at a risk level of acceptable environmental risk. Releases, regular and accidental should be controlled in such a manner that the surrounding environment will not suffer by the ship activity (Papanikolaou, 2009).

4.3 PROBABILISTIC DAMAGE STABILITY

Probabilistic damage stability (PDS) is a methodology based on accident statistics on ship-ship collisions. For each casualty, the size and location of the damage, and whether the vessel has sufficient buoyancy to remain afloat after the damage has occurred is noted. The location of damage is the location on the vessel, not to be confused with the area the vessel operates in. The philosophy behind the method is that two different ships with the same attained index of subdivision are equally safe. The initial ideas of regulations for damage stability that would be based on accidents statistics came from the German professor Kurt Wendel in 1960. He published an article with the title ''The Probability of Survival from Damages''. The International Maritime Organization (IMO) has later developed probabilistic regulations for damage stability based in this approach. The foundation for the probabilistic method is the probability that the vessel will suffer a certain damage multiplied with the survivability of the vessel after the damage has occurred. The method calculates the individual probabilities for all possible damage cases the ship can encounter multiplied with the survivability of each individual damage case. Survivability is defined as the vessels capability to stay afloat after being rammed by an arbitrary ship. The attained index, A, is the summation of the probability and survivability for all the possible damage cases. This attained index describes whether the vessel can sustain certain damages in a sufficient manner to ensure the safety of the crew and passengers aboard. The probabilistic damage stability regulations require that the value of the attained index is at least the value of the required index, R. The required index is easily calculated for each vessel based on the ship length and the number of passengers the vessel can carry (passenger vessels) (Olufsen and Hjort, 2013)

In order to fully understand probabilistic damage stability, it is vital to comprehend where the method came from. Deterministic damage stability (DDS) was the dominating method for damage stability calculations before PDS. Ship stability is defined as the ship's capability to return to its initial upright position after a force, external or internal, has been applied on the ship. There are two main elements to evaluate the stability of the vessel, moment acting on the vessel due to acting force and the righting moment. The righting moment is defined by the hull shape and geometry of superstructure, whereas the acting moment can be wind, sea conditions or water intrusion that causes the ship to heel (Sillerud et al., 2011). Intrusion of water is the dominating factor that influences the damage stability of the vessel. The main principles for calculation on stability are the acting gravity force and the change of buoyancy forces. All compartments under the waterline contribute to the buoyancy acting on the vessel. If a compartment is bilged, water will fill the volume and the vessel loose buoyancy that causes the vessel to sink down. The underwater volume increases so the buoyancy force increases accordingly until equilibrium with the gravity force. In case of damage to either side of the vessel, the ship will heel over because of unsymmetrical buoyancy. If the damage causes loss in buoyancy that is larger than the remaining buoyancy, the vessel will ultimately sink. Regulations for damage stability were formulated to limit the risk of sinking and ensure the safety of people aboard. The deterministic damage stability method controls if the ship is safe enough. The method calculates if the ship can withstand certain damage scenarios depending on the ship beam and length. Calculations are made for different damage conditions and the vessel should fulfil the criteria's given by SOLAS in order to be certified by the classification societies. The requirements for DDS are dependent on vessel type, number of passengers, cargo, etc. The parameters are the same for a each ship type but will change in magnitude (Patterson and Ridley, 2014). The advantage for DDS is that the calculations do not require advanced damage stability calculations, and the method gives a rapid impression of the ship's capabilities to withstand damage. However, the method gives little flexibility in the design and the deterministic rules cannot be used as a quantification of risk (Olufsen and Hjort, 2013).

It has been demonstrated in several accidents that the concept of rule damages of a predefined size, such as in DDS, is not sufficient in real life accident scenarios. This has led to the development of probabilistic damage stability regulations. The first implementation of the regulations was done in the early 1970s in IMO Resolution A.265 as an alternative to the deterministic damage stability regulations for passenger vessels. The probabilistic approach was, however, seldom used as the method involved heavier demands and considered more damage cases than the deterministic approach. (Lauridsen et al., 2001). As mentioned, Harmonization of Rules and Design Rationale (HARDER) and Goal Based Damage Stability (GOALDS) are research projects performed with the objective to improve the regulations regarding probabilistic damage stability. The projects have been funded by EU and commercial partners to increase the knowledge and understanding of ship casualties in order to develop regulations that represent the accidents statistics in the best possible manner. The HARDER project worked to harmonize the damage stability regulations for all ship types using the probabilistic approach. The harmonized regulations were implemented in SOLAS in January 2009 (Papanikolaou, 2009). The GOALDS project attempted to address the shortcomings of SOLAS 2009 due to concerns regarding the calculated survivability of passenger vessels and that the approach only considered ship-ship collisions, as a large part of the maritime accidents are related to grounding accidents. The project updated the damage statistics on collision damage and developed a database on grounding casualties. The updated database did not lead to significant changes in the probabilistic distributions for collision damages. It did, however, lead to the development of probability distributions of bottom damages due to grounding accidents. The probability density functions developed can be used in combination with Monte Carlo simulation to obtain an index for survival of grounding damages (Papanikolaou et al., 2012).

The attained index measures the residual stability of the vessel considering all possible sizes of the damage. Each of the damages are weighted by the probability that such a damage can be expected, measured in terms of the factor P. The survivability of the vessel after the damage has occurred, is measured in terms of the factor S, and calculated from the properties on the associated residual stability curve. The factors S and P does not take the vertical extent of damage into consideration, thus a factor V is implemented in the calculations. V represents the probability that a vertical deck above the waterline will remain intact after the damage has occurred. Thousands of damage cases must be considered for probabilistic damage stability calculations on a vessel, necessitating extensive use of dedicated computer programs for accurate calculations (Lauridsen et al., 2001).

Probabilistic damage stability gives more freedom in the design since the designer is not obliged to follow the damage extents known from deterministic damage stability. As mentioned, when following the probabilistic damage stability regulations, the attained index, A, needs to fulfil the requirement of the required index R in equation 4.

$$A \geq R \qquad Eq. 4$$

In order to calculate A, the length of the ship is divided into a discrete number of damage zones. Figure 11 illustrates the possible single- and multiple damage zones on a vessel with watertight a arrangement for a seven-zone division. The triangles signify single zone damages while the parallelograms signify combinations of neighbouring damages. In a damage zone report from probabilistic damage stability calculations, the zone report is presented in a diagram as in figure 11. The possible severities of the different damages are differentiated by different colours in the diagram, e.g. where green represent damages with high probability of survival and red represent damages with low probability of survival.

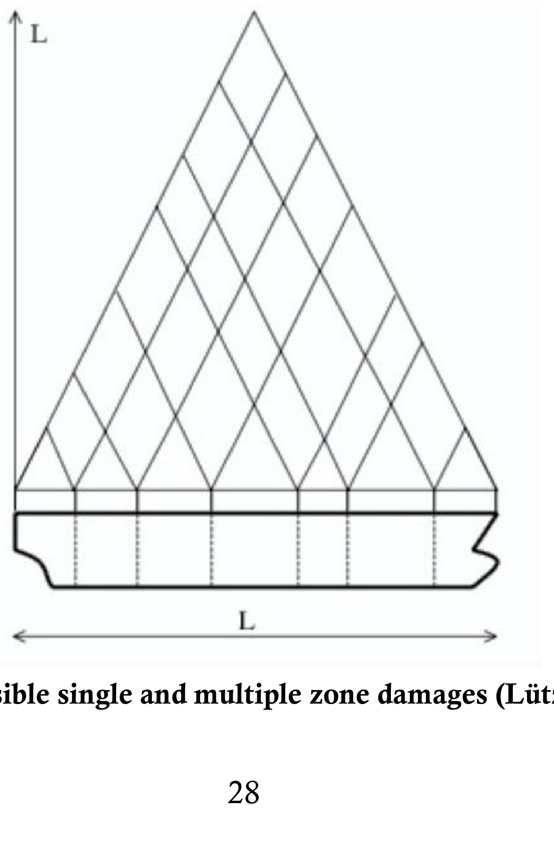

Figure 11: Possible single and multiple zone damages (Lützen, 2001)

It is not obvious how to use the regulations in a conceptual design process to obtain the most appropriate subdivision, as the method only results in a single measure in the attained index. The regulations for the calculation of the required and attained index are thoroughly described in the following sub-chapters. The regulations on probabilistic damage stability are taken from SOLAS chapter II-1 Part B: Stability. The explanatory notes on the probabilistic damage stability rules in SOLAS have been used to verify the interpretation of the regulations. A calculation on a specific damage case is presented in chapter 5.6. As the regulations can be difficult to comprehend, it can support the understanding of the regulations by looking at a calculated damage case.

4.3.1 Regulation 6 – Required subdivision index R

The required index for passenger vessels was formed through the HARDER project. Based on calculations on a sample of 40 passenger ships and 92 dry cargo ships, the degree of subdivision to be provided was proposed by formulas for the required subdivision index R. The subdivision length, Ls, is based on the buoyant hull and the reserve buoyancy of the hull. Explanation of how the subdivision length is found is presented in appendix B (Olufsen and Hjort, 2013). The formula is divided into three categories; passenger ships, cargo ships between 80 and 100 m and cargo ships larger than 100 m. The formula for passenger ships is calculated using equation 5 and depends on ship length and number of passengers the ship is certified for (IMO, 2014).

$$R = \frac{5000}{L_S + 2.5N + 15225} \qquad Eq. 5$$

$N - N_1 + 2N_2$
$N_1 - Number\ of\ persons\ for\ whom\ lifeboats\ are\ provided$
$N_2 - Number\ of\ persons\ the\ ship\ is\ permitted\ in\ excess\ of\ N_1$
$L_S - Ship\ length$

The required index for cargo ships is only dependent on ship length. For cargo ships greater than 100 m in length, the required index R is calculated using equation 6 (IMO, 2014).

$$R = 1 - \frac{128}{L_S + 152} \qquad Eq. 6$$

In the case of cargo ships less than 100 m in length and not greater than 80 m in length, R is calculated using equation 7 (IMO, 2014).

$$R = 1 - \frac{1}{1 + \frac{L_S}{100} \times \frac{R_0}{1 - R_0}} \qquad Eq.7$$

$R_0 - The\ value\ of\ R\ calculated\ in\ equation\ 6$

4.3.2 Regulation 7 – Attained subdivision index A

The attained subdivision index A is calculated for multiple damage scenarios depending on the geometric complexity of the watertight arrangement on the vessel. The calculation of A requires understanding of the ships parameters and divisions, and which formulas to use for different vessel types. The attained index is acquired by the summation of the partial indices for three predefined service draughts according to equation 8(IMO, 2014).

$$A = 0.4A_s + 0.4A_p + 0.2A_l \qquad Eq.8$$

$A_s - Attained\ index\ for\ deepest\ subdivision\ draught$
$A_p - \ Attained\ index\ for\ partial\ subdivision\ draught$
$A_l - Attained\ index\ for\ lightest\ service\ draught$

The attained indices are multiplied with factors representing the operation time in each loading condition. The factors are based on the assumption that the vessel operates 40% of its operation time in the deepest load line condition, 40% in the partial condition and 20% in the lightest service draught condition.

For each partial index, the summation of all the possible damage cases must be calculated on the basis of the probability and survivability of damage, multiplied with the probability that the space above the horizontal subdivision will stay intact. The final attained index is calculated using equation 9 for the three draughts, and implementing the three attained indices in equation 8.

$$A_C = \sum_{1}^{i=t} P_i S_i V_i \qquad Eq. 9$$

$A_C - Attained\ index\ for\ particular\ loading\ condition$
$i - Damage\ or\ damage\ zone\ under\ consideration$
$t - Number\ of\ damages\ that\ has\ to\ be\ investigated$
$P - Probability\ for\ damage$
$S - Survivability$
$V - Probability\ for\ the\ compartments\ above\ the\ horizontal\ divisons\ to\ stay\ intact$

To summarize, the P_i component depends on the geometry of the watertight arrangement of the ship and is a factor for the probability of suffering a specific damage. The S_i component depends on the survivability of the vessel after the damage has occurred for a specific damage case. The component V_i is implemented to include the vertical extent of the damage since P_i and S_i only includes the longitudinal and transverse extent. The V_i factor represents the probability that a deck above the damage will remain intact. The following paragraphs will explain the calculations behind these components. The definition of the different factors is repeated to ensure the reader's understanding of the central factors in the probabilistic damage stability regulations.

4.3.3 Regulation 7-1 – Calculation of the factor P_i

P_i is the probability of a specific damage on the vessel, i.e. that a compartment or group of compartments are flooded. The factor is solely dependent on the geometry of the watertight arrangement. The formula for calculation of P_i is shown in equation 10 (IMO, 2014).

$$P_i = p(x1_j, x2_j) \cdot [r(x1_j, x2_j, b_k) - r(x1_j, x2_j, b_{k-1})] \qquad Eq. 10$$

$J - The\ aftmost\ damage\ zone\ number\ involved\ in\ the\ damage\ starting\ with\ no. 1\ at\ stern$
$K - Number\ of\ particular\ longitudinal\ bulkhead\ as\ barrier\ for\ transverse\ penetration$
$x1 - Distance\ from\ aft\ end\ of\ the\ ship\ the\ aft\ end\ of\ the\ zone\ in\ question$
$x2 - Distance\ from\ aft\ end\ of\ the\ ship\ to\ the\ forward\ end\ of\ the\ zone\ in\ question$
$b - Mean\ transverse\ distance\ from\ shell\ to\ longitudinal\ barrier$
$r - Factor\ to\ account\ for\ the\ transversal\ extent\ of\ damage$

The formula in equation 10 applies for damages of single zones only. The equation for multi-zone damages can be found in SOLAS Chapter II-1, regulation 7-1.

p(x1, x2) is an expression for the probability of damage length in the longitudinal direction. The data on damage lengths collected from the HARDER project is illustrated in figure 12. The blue plots illustrate the damage lengths as a function of the struck ship's length. The work concluded in that the deterministic damage length used in the present SOLAS passenger ships regulations (0.03L + 3m, max 11m) did not give satisfactory results when compared to the actual damage length collected from collision accidents. The damage lengths were normalised with respect to damage length in order to derive formulas for the probabilities. The probability distribution is shown in figure 13. The probability density function, Pdf, is represented on the y-axis and the values on the x-axis are the non-dimensional damage length, J.

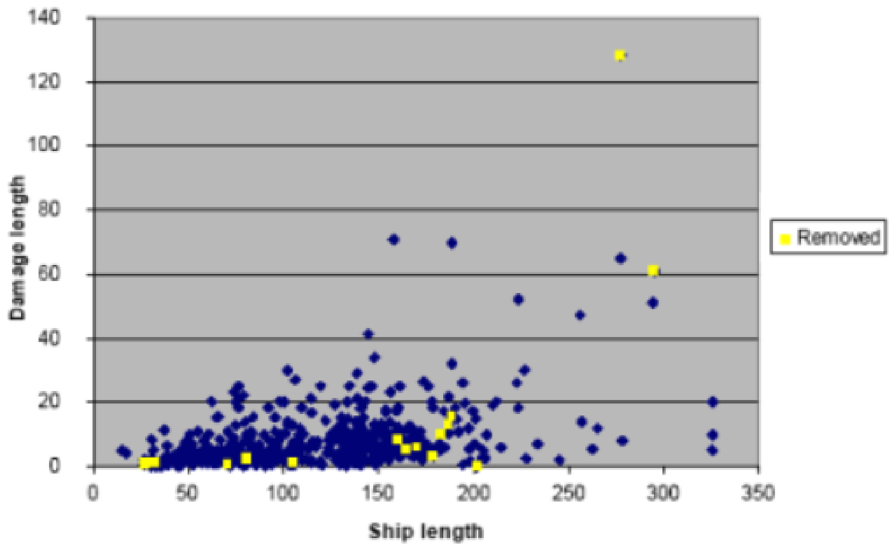

Figure 12: Damage length vs. ship length (Olufsen and Hjort, 2013)

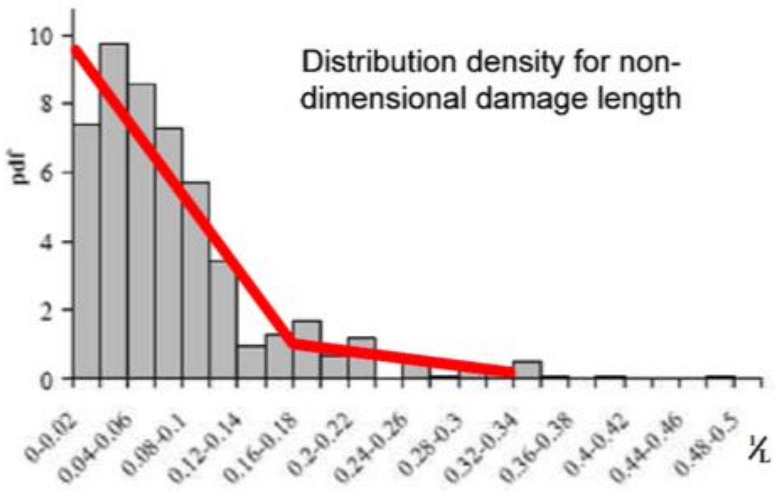

Figure 13: Probability density function of damage length (Olufsen and Hjort, 2013)

The thick red line in figure 13 represents the distribution as applied in the probabilistic damage stability regulations. One of the objectives for the HARDER project was to collect information about earlier damage cases and find a correlation between damage length, ship length and damage location. The work concluded in that the damage location distribution was not significant. To simplify the calculations, the non-dimensional damage location was set equal to 1, signifying an equal probability for damage along the whole ship length (Lützen, 2001).

The values in table 3 represent the red line in figure 13. J_{max} is the crossing point between the red line and the x-axis. The value represents the non-dimensional damage lengths a ship can encounter. J_{kn} represent the knuckle point on the curve and P_k is the cumulative probability at this point (IMO, 2014).

Table 3: Non-dimensional damage lengths (IMO, 2014)

Overall normalized max damage length, J_{max}	Knuckle point in the distribution, J_{kn}	Cumulative probability at J_{kn}, P_k	Maximum absolute damage length, l_{max} [m]	Length where normalized distribution ends, L* [m]
10/33	5/33	11/12	60	260

A bi-linear function has been used to describe the non-dimensional damage length. The parameters are described as fractions as it was considered easier to implement in the regulations. These bi-linear functions in equation 11, proposed by Lützen, were implemented in the SOLAS revision.

$$b(x) = \begin{cases} b_{11} \cdot x + b_{12} \ for \ x \leq J_k \\ b_{21} \cdot x + b_{22} \ for \ x > J_k \end{cases} \qquad Eq. 11$$

J_k $-$ *Knuckle point on the red curve*
$x - non - dimensional\ damage\ length$

The subsequent coefficients are derived using the non-dimensional damage lengths in table 3 and the bi-linear function in equation 11.

$$b_{11} = 4\frac{1 - p_k}{(J_m - J_k)J_k} - 2\frac{p_k}{{J_k}^2} \qquad b_{12} = independent\ on\ ship\ lenght$$

$$b_{21} = -2\frac{1 - p_k}{(J_m - J_k)^2} \qquad b_{22} = -b_{21}J_m$$

The J_m factor in the expressions for the coefficients is the maximum non-dimensional damage length for the ship under consideration, and J_{kn} is the knuckle point in the distribution. As the damage statistics varies with ship length, the factors J_m, J_k and b_{12} varies consequently (IMO, 2014).

In cases where $L_s \leq L^*$:

$$J_m = \min\left(J_{max}, \frac{l_{max}}{L_s}\right)$$

$$b_{12} = b_0 = 2\left(\frac{p_k}{J_{kn}} - \frac{1 - p_k}{J_{max} - J_{kn}}\right)$$

$$J_k = \frac{J_m}{2} + \frac{\sqrt{1 + (1 - 2p_k)b_0 J_m + \frac{1}{4}{b_0}^2 {J_m}^2}}{b_0}$$

If L_s is below 198 m, J_{max} will be the smallest value and consequently used for J_m. Thus J_k will be constant for all vessels below 198 m (Djupvik, 2014).

In the cases where $L_s > L^*$ the two factors J_m^* and J_k^* are used as the number of damages for vessels with a length above L* (260 m) are low, causing deviations in the distribution functions. As a solution, the distribution functions only yield for vessels with length less than L*. In cases where the ship length is greater than L*, the factors J_m^* and J_k^* are used and converted to J_m and J_k according to the following calculations (Olufsen and Hjort, 2013).

$${J_m}^* = \min\left(J_{max}, \frac{l_{max}}{L^*}\right)$$

$${J_m}^* = \frac{l_{max}}{L^*}$$

$$J_m = \frac{{J_m}^* \cdot L^*}{L_s}$$

$${J_k}^* = \frac{{J_m}^*}{2} + \frac{\sqrt{1 + (1 - 2p_k)b_0 {J_m}^* + \frac{1}{4}{b_0}^2 {J_m}^{*2}}}{b_0}$$

$$J_k = \frac{J_k{}^* L^*}{L_s}$$

$$b_{12} = 2\left(\frac{p_k}{J_k} - \frac{1 - p_k}{J_m - J_k}\right)$$

When J_m, J_k and b_{12} are found, the normalized damage length, J_n can be calculated. J_n is used to calculate p(x1, x2) (IMO, 2014).

$$J = \frac{(x2 - x1)}{L_s} \qquad\qquad J_n = \min\{J, J_m\}$$

$J - \textit{the non dimensional damage length}$
$J_n - \textit{the normalized lenght of a compartment or group of compartments}$

Which equation for calculating p(x1, x2) is dependent in the damage case considered. The three different alternatives are presented (IMO, 2014):

In cases where neither limits of the compartment or group of compartments under consideration coincides with the aft or forward terminal. In other words, if the damage under consideration is not located at the aft or forward end of the vessel, p(x1 ,x2) should be calculates using equation 12.

$J \leq J_k : \; p(x1, x2) = p_1$

$$p_1 = \frac{1}{6} J^2 (b_{11} J + 3 b_{12}) \qquad Eq. 12$$

$J > J_k : \; p(x1, x2) = p_2$

$$p_2 = -\frac{1}{3} b_{11} J_k{}^3 + \frac{1}{2}(b_{11} J - b_{12}) J_k{}^2 + b_{12} J J_k - \frac{1}{3} b_{21}\left(J_n{}^3 - J_k{}^3\right) + \frac{1}{2}(b_{21} J - b_{22})\left(J_n{}^2 - J_k{}^2\right) + b_{22} J (J_n - J_k) \qquad Eq. 12$$

In cases where one of the sides, forward or aft, of the compartment or group of compartments coincides with the forward or aft terminal. In other words, if the damage under consideration is located either at the aft end or at the forward end of the vessel, p(x1, x2) should be calculated according to equation 13, where p_1 and p_2 are calculated as in equation 12.

$J \leq J_k$

$$p(x1, x2) = \frac{1}{2}(p_1 + J) \qquad Eq. 13$$

$J > J_k$

$$p(x1, x2) = \frac{1}{2}(p_2 + J) \qquad Eq. 13$$

In cases where one of the compartment or group of compartments considered extends over the entire subdivision length Ls, p(x1 ,x2) should be calculated using equation 14.

$$p(x1, x2) = 1 \qquad Eq. 14$$

4.3.4 Calculation of the $r(x1_j, x2_j, b_k)$ factor

The factor r is the probability that a penetration is less than a given transverse breadth, b. The factor is based in damage statistics using the same approach as the p(x1 ,x2) factor. Equations for calculating $r(x1_j, x2_j, b_k)$ are derived from damage statistics of more than 400 cases presented in figure 14. The data is collected by the HARDER project and presented as damage penetrations as a function of the ships' breadth. The line dividing the penetrations at the B/5 limit is implemented for comparison. The B/5 limit is used in the deterministic regulations.

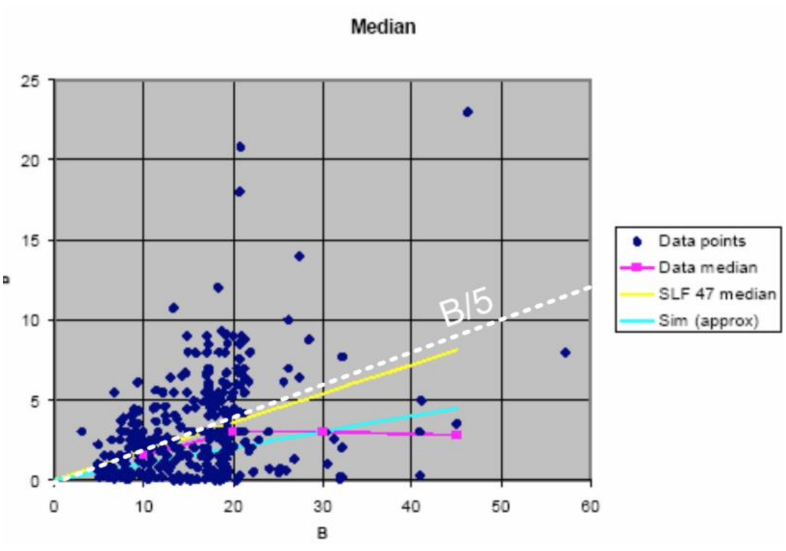

Figure 14: Damage penetration as function of breadth (Olufsen and Hjort, 2013)

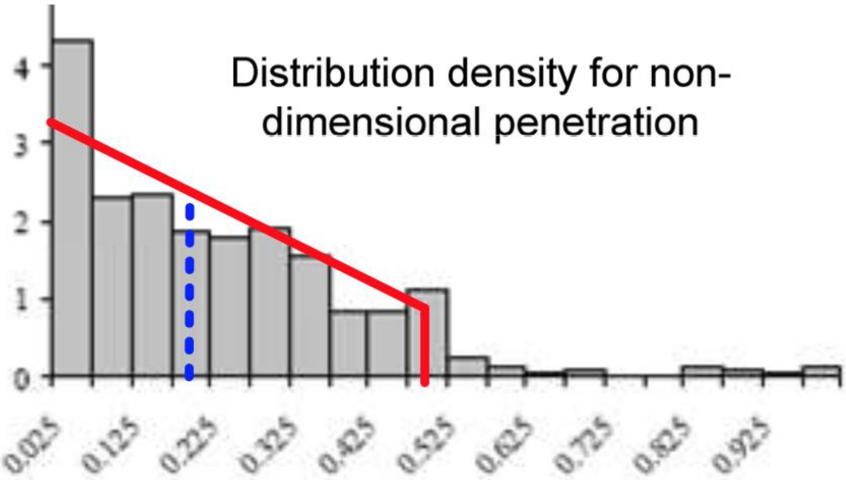

Figure 15: Density distribution for non-dimensional penetration (Olufsen and Hjort, 2013)

Figure 15 presents the non-dimensional penetration with the probability density function on the y-axis and the ratio between penetration depth and ship breath on the x-axis. The penetration depth b, is measured from the deepest subdivision draught as a transverse distance from the ship side, normal to the centreline, to the longitudinal barrier. In cases where the longitudinal barrier is not parallel to the ship hull, an assumed line should determine the distance b.

Calculation of the r factor is done using equation 15 (IMO, 2014):

$$r(x1, x2, b) = 1 - (1 - C) \cdot \left[1 - \frac{G}{p(x1, x2)}\right] \qquad Eq. 15$$

$C = 12 \cdot J_b \cdot (-45 \cdot J_b + 4)$

$J_b = \dfrac{b}{15B}$

$b - Penetration\ depth$

$B - Maximum\ ship\ beam\ at\ deepest\ draught$

When calculating G in $r(x1_j, x2_j, b_k)$, the same conditions are used as for the selection of p(x1, x2) in chapter 4.3.3 (IMO, 2014):

In the case where the compartment or groups of compartments considered extends over the entire subdivision length, G should be calculated using equation 16.

$$G = G_1 = \frac{1}{2} b_{11} J_b{}^2 + b_{12} J_b \qquad Eq.16$$

In the case where neither limit of the compartment or group of compartments under consideration coincides with the aft or forward terminals, G should be calculated using equation 17.

$$G = G_2 = -\frac{1}{3} b_{11} J_0{}^3 + \frac{1}{2}(b_{11} J - b_{12}) J_0{}^2 + J b_{12} J_0 \qquad Eq.17$$

$J_0 = min\{J, J_b\}$

In the case where the aft limit of the compartment or group of compartments under consideration coincides with the aft terminal, or the forward limit of the compartment of group of compartments under consideration coincides with the forward terminal, G should be calculated using equation 18.

$$G = \frac{1}{2}(G_2 + G_1 J) \qquad Eq.18$$

A more thorough explanation and derivation of the formulas for p(x1, x2) and the r factor can be found in Marie Lützen's PhD thesis, ''Ship Collision Damage''.

4.3.5 Regulation 7-2 – Calculation of the S_i factor

The S_i factor is dependent on the survivability of the vessel after a specific damage has occurred. A survivability factor of 1 denote that the vessel will survive flooding of the specific damage case, while a factor of 0 denotes that the vessel will not survive. The factor is calculated using equation 19 (IMO, 2014):

$$S_i = min\{S_{intermediate,i}, S_{final,i} \cdot S_{mom,i}\} \qquad Eq.19$$

$S_{intermediate,i}$ – $probability\ to\ survive\ all\ intermiediate\ flooding\ stages\ until\ the\ final\ equilibrium\ stage$

$S_{final,i} - probability\ to\ survive\ in\ the\ final\ equilibrium\ stage\ of\ flooding$
$S_{mom,i} - probability\ to\ survive\ heeling\ moments$

To collect data, the HARDER project investigated the wave height distributions at the time of the accidents in the casualty database. The project suggested that within a sea state range between 0 to 4 m, the proposed GZ criteria would be rather accurate for prediction of the vessel's survival. GZ is the distance of the righting arm that gives a righting moment on the vessel using the buoyancy force. There are no requirements for stability in the intermediate stage for cargo ships, i.e. for cargo ship $S_{intermediate,i}$ is set equal to 1. The heeling angle $GZ_{max,}$ range of positive GZ and the equilibrium of the heeling angle make the foundation for the calculation of S. Several of the criteria in regulation 7-2 appear as deterministic. The probabilistic element enters with the probability of successful evacuation that will increase if the static heeling angle is low and if the evacuation route will not be impeded by water. The S factor is highly related to the distribution of residual buoyancy, it is therefore combined with the probability that the watertight decks will remain intact.

S_{final} is calculated using equation 20 (IMO, 2014):

$$S_{final} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16}\right]^{\frac{1}{4}} \qquad Eq.20$$

$$K = \sqrt{\frac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$$

$K = 1\ if\ \theta_e \leq \theta_{min}\ , K = 0\ if\ \theta_e \geq \theta_{max}$

$\theta_e - Equilibrium\ heeling\ angle\ after\ damage$

$\theta_{min} - Minimum\ heeling\ angle$

$\theta_{max} - Maximum\ heeling\ angle$

$Passenger\ ships: \theta_{min} = 7\ degrees\ and\ \theta_{max} = 15\ degrees$

$Cargo\ ships: \theta_{min} = 15\ degrees\ and\ \theta_{max} = 30\ degrees$

$Range - The\ range\ with\ positive\ righting\ arm$

The K value is based on the obtained heeling angle and is applied to give satisfactory heeling angles for the different ship types. The equation above shows that if the vessel heel more than 15 degrees for passenger vessels and 30 degrees for cargo vessels, the value of S_i will be equal to 0. The ship designer has to be cautious when designing the arrangement in order to prevent larger heeling angles than the maximum values. The damage states for such scenarios would not contribute to the attained index. It is a common design measure to leave out longitudinal bulkheads in the double bottom in order to get symmetrical damages and thus avoid excessive heeling (Djupvik, 2014).

GZmax is measured in meters and is the maximum righting arm. The value should be between θ_e and θ_v, where θ_v is the angle where GZ gets negative or when a non-watertight opening is submerged. Range is measured in degrees and is the distance between θ_e and θ_v. A typical GZ curve is illustrated in figure 16, where the different parameters mentioned are displayed. Figure 17 illustrates a case where GZ_{max} is reached before the actual GZ_{max} for the vessel, caused by an opening being submerged when the heeling reaches the θ_v value. Designers locate all openings a certain distance above first deck to avoid this scenario of cutting the GZ curve before reaching maximum value (Djupvik, 2014).

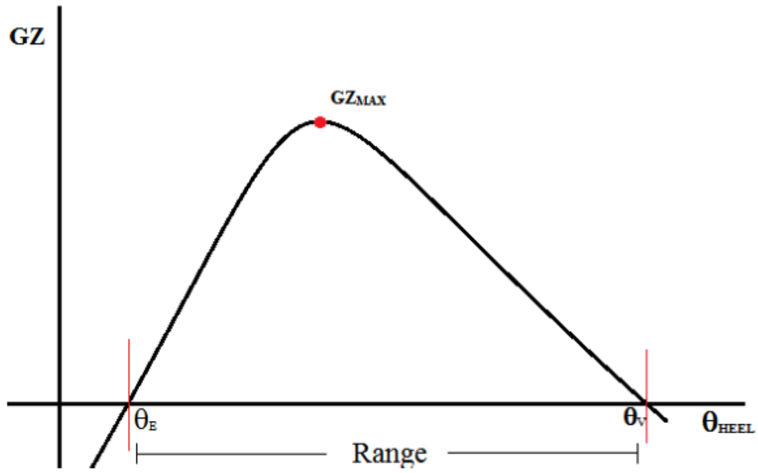

Figure 16: GZ curve (Djupvik, 2014)

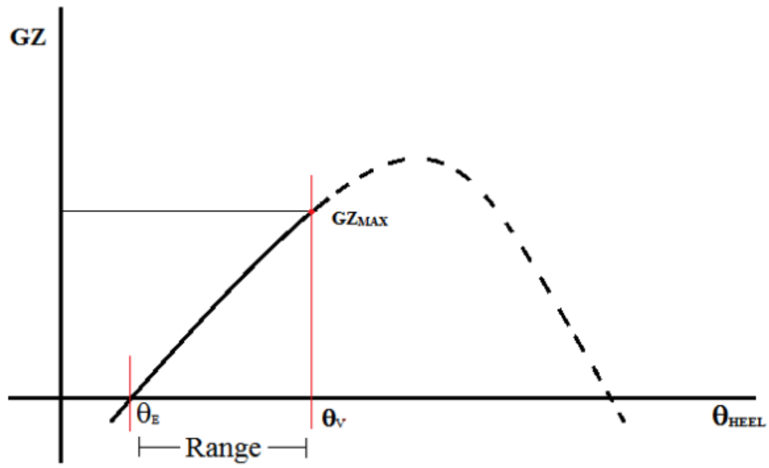

Figure 17: GZ curve submerged opening (Djupvik, 2014)

$S_{intermediate,i}$ is only calculated for passenger vessels and is calculated using equation 21 (IMO, 2014):

$$S_{intermediate} = \left[\frac{GZ_{max}}{0.05} \cdot \frac{Range}{7}\right]^{\frac{1}{4}} \qquad Eq. 21$$

GZ_{max} *is not to be taken as more than* $0.05m$
Range is not to be taken more than 7 *degrees*
$S_{intermediate} = 0$ *, if the heeling angle exceeds* 15 *degrees*

$S_{intermediate,i}$ is calculated similar to the calculation of S_{final} for all intermediate stages of flooding.

$S_{mom,i}$ is the probability to withstand heeling moments from wind, movement of passengers or movement of survival crafts. The calculations for $S_{mom,i}$ are based on the vessel's displacement, GZ_{max} and M_{heel}. For cargo vessels $S_{mom,i}$ is always set equal 1. For passenger vessels, the factor is calculated using equation 22 (IMO, 2014):

$$S_{mom,i} = \frac{(GZ_{max} - 0.04) \cdot Displacement}{M_{heel}} \qquad Eq. 22$$

$M_{heel} = \max\{M_{passenger}, M_{wind}, M_{survival\ craft}\}$
$S_{mom} \leq 1$*, the factor can never have a value larger than* 1
$M_{passenger} = (0.075 \cdot N_p) \cdot (0.45 \cdot B)$
N_p *— maximum number of passengers permitted*
B *— ship beam*
$M_{wind} = \frac{P \cdot A \cdot Z}{9.806}$
$P = 120 \frac{N}{m^2}$
A *— projected wind area*
Z *— Distance from projected wind area to* $\frac{T}{2}$
T *— Ship draught*

$M_{survivalcraft}$ is the maximum assumed heeling moment from launching a fully loaded survival craft on one side of the ship. After calculating the three moments, the maximum of the values is used as M_{heel}.

4.3.6 Regulation 7-2 – Calculation of the V_i factor

The V_i factor is the probability that a deck above the waterline will not be breached after an arbitrary ship has struck the ship. V_i is implemented in order to account for contributions from the horizontal divisions, as the buoyancy above the waterline will affect the residual ship stability. If a compartment above the waterline is submerged, it will influence the buoyancy, thus influencing the GZ-curve, and thus affecting the S factor. The V_i factor is calculated using equation 23 (IMO, 2014):

$$V_i = v\left(H_{m,d}\right) - v(H_{(m-1),d} \qquad Eq. 23$$

$H_m -$ *Least height to first horizontal boundary above the waterline, measured from the baseline. The horizontal boundary must limit the extent of flooding vertically and and be within the longitudinal range of the damage*

$H_{m-1} -$ *Least height to $(m-1)$horizontal boundary above the waterline, measured from the basline. The horizontal boundary must limit the extent of flooding verticallyand be within the longitudinal range of the damage*

$m -$ *Horizontal boundary upwards from the waterline*
$d -$ *Draught*
V_i *should in no cases be taken as less than zero or more than one*

v(H_m, d) and v($H_{(m-1)}$, d) are calculated as follows (IMO, 2014):

$$For\ (H-d) < 7.8: \qquad v(H,d) = 0.8\,\frac{(H-d)}{7.8}$$

$$For\ (H-d) \geq 7.8: \qquad v(H,d) = 0.8 + 0.2\,\frac{(H-d) - 7.8}{4.7}$$

$$v\left(H_{m,d}\right) = 1 \quad if\ H_m\ coincides\ with\ the\ uppermost\ waterthight\ boundary\ of\ the\ ship\ within\ the\ longitudinal\ range\ of\ the\ damage$$

$$v\left(H_{0,d}\right) = 0$$

Equation 23 is developed using the statistics collected from the HARDER project presented in figure 18 below. The red line in figure 18 represents the formula for Vi where (H – d) is the distance between the initial waterline and the horizontal limit above the damage. The damage extent is limited to 12.5 m above the waterline.

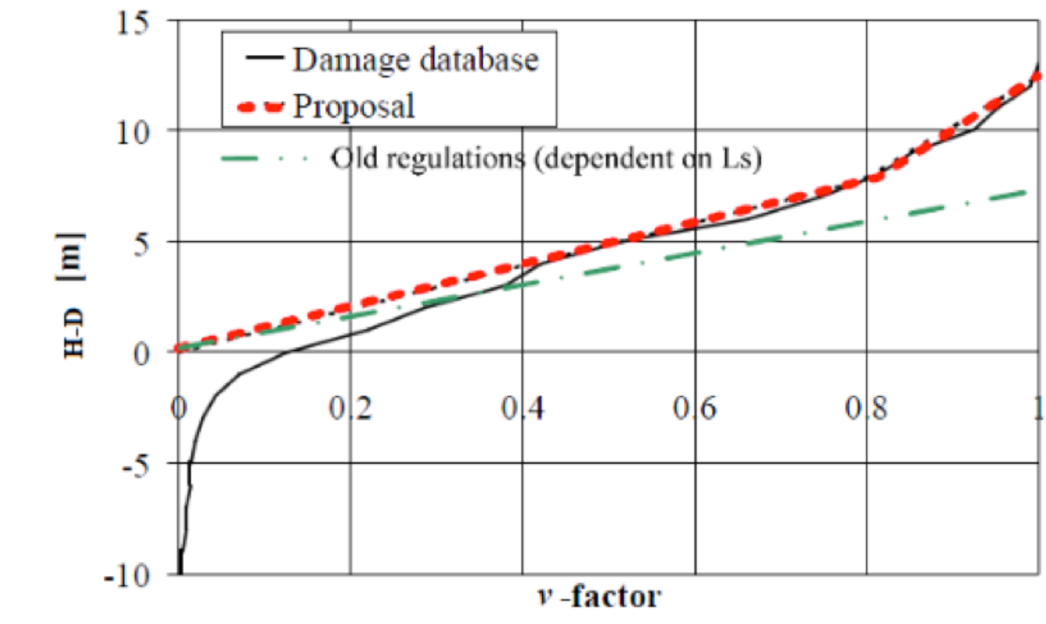

Figure 18: Vertical damage distribution (Olufsen and Hjort, 2013)

When calculating the V_i factor for a specific damage case, the decks that must be considered are the ones affected by the damage, located above the waterline. Affected is meant by the decks that are connected to the damage, i.e. the decks that have been breached by the damage and the top deck that limits the damage.

4.3.7 GM limiting curve

Metacentric height (GM) is the distance from the vessel's centre of gravity to its metacentre. A large GM value implies great initial stability, as the ability to return to upright position after being exposed for an external force causing the vessel to heel is great. The GM value affects the natural period of roll where large values are associated with short roll periods, which can be uncomfortable for passengers and crew. Passenger vessels are therefore usually designed with GM values that are sufficiently high, but not as high that it will cause rapid roll motions under operation.

There is a requirement that the ship has to operate within the GM limiting curve. The minimum curve defines the vessel's acceptable operational area, and is dependent on draught, trim and the vertical centre of gravity. The limiting curve should be used when determining the loading conditions for the vessel under consideration. Loading conditions with a GM above the limit curves ensures that the vessel operates under compliance with the stability criteria. The GM values used for calculation of the attained index are the basis for the limiting curves that the vessel has to operate within. Figure 19 present an example for a GM limiting curve.

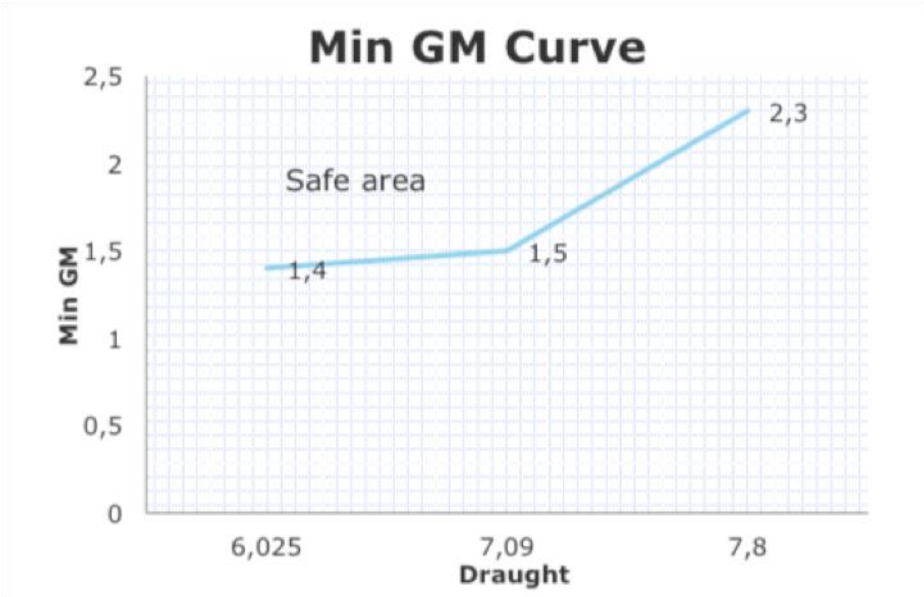

Figure 19: GM limit curve (Olufsen and Hjort, 2013)

The calculations on the deepest and partial draught are normally done for level trim. At the lightest service draught the actual trim may be used (Olufsen and Hjort, 2013).

4.4 PDS AS A TOOL IN A RISK ANALYSIS

Probabilistic damage stability can be used as a tool in a risk analysis by quantifying risk and evaluating risk control options (RCOs) for risk reduction. Changes in the watertight arrangement can be evaluated using software for PDS calculations such as NAPA or DELFTShip. The changes will result in a change in the attained index calculated by the software. The arrangement with the highest attained index is considered safest or most acceptable according to the regulations. Then calculations can be made for the evaluation of the benefit of the change using cost benefit analysis. Based on results from the cost benefit analysis, the designer can give recommendations for decision-making regarding the changes.

In order to implement the change in the attained index to the risk assessment, the difference in A must be transformed to be a quantity of reduced risk. By implementing the measures, the vessel should have improved damage stability after flooding. The increased level is expressed by the attained index A, and the improvements will impact the probability of staying afloat after the vessel has sustained damage. According to the concept behind the framework for PDS, the attained index of the vessel can be interpreted as the share of all potential collisions resulting in water ingress and flooding the survival time would be 30 minute or more. For instance, if a ship has an attained index of 0,78, it is interpreted as that in 78% of all potential collisions the survival time is 30 minutes or more. In the remaining 22% of the collisions the survival time is less than 30 minutes (Guarin et al., 2009). In the analysis performed in the following chapter, it is assumed that the attained index is a measure of damage stability, thus a design measure for risk reduction will lead to higher probability of remaining afloat. So, in the analysis, if by implementing a risk reduction measure causing an increase in the attained index from 0,78 to 0,90, the new probability in the event tree for remaining afloat will be increased by 15%.

DELFTShip is used as the stability software in the case study. However, the general ship designer opinion is that DELFTShip is not as reliable as NAPA for complex ship arrangements. NAPA is widely used in the ship design industry and is considered as a reliable tool for stability calculations. DELFTShip, on the other hand, is more accessible and easier to use, but is not accepted as a sufficient tool for stability calculations in the maritime industry. Calculations on a simple damage case is done by hand and compared with DELFTShip to verify the reliability of the software in chapter 5.6. It has not been possible to get a license to use NAPA for the thesis work, thus the stability software has not been considered further.

CHAPTER 5

CASE STUDY: EVALUATING THE EFFECT OF RISK REDUCTION USING PDS

5.1 RISK MODELLING

On the basis of the information gathered in chapter 3, it is assumed that an impact scenario with drifting ice such as bergy bits and growlers are likely to occur when operating in areas near Svalbard and Greenland. These areas are popular for cruise tourism during the summer months, and there have been occurrences of standard cruise vessels that sail in these areas from during this period. Standard cruise vessels, vessels designed for open water without ice class, operating in the ice free waters are even more exposed to the dangers of encountering drifting ice, as the hull will not be able to withstand the ice loads as well as vessels with ice class. However, most of the Arctic cruise vessels are designed for the Arctic conditions with ice class, enforcing the hull to manage higher loads from ice. The study on impact loads from bergy bits and growlers show that even small ice pieces can result in high loads on the ship hull when sailing in normal transit speed. An impact incident that result in flooding of one ore more compartments can have major consequences. It is therefore essential to evaluate measures for improved damage stability.

The motivation for this thesis is to use PDS as a tool in a risk analysis and evaluate measures for improved damage stability related to cruise ship operation in Arctic. Therefore, in this analysis, it is assumed that the cruise vessel is sailing in a field with drifting bergy bits and growlers. The analysis only considers impact with ice pieces calved from icebergs, as they are stronger than ice pieces formed from sea ice, and will therefore induce larger impact forces. A fault tree diagram for the impact scenario is illustrated in figure 20. The events in the fault tree are explained in the following. Basic event 1, wrong reaction, considers human decisions and misinterpretations of the situation. The bergy bits and growlers can be difficult to detect by the crew and systems aboard. Weather conditions such as fog, snow and wind render it difficult to detect small objects by the operating crew, this is considered in basic event 2. Current marine radar systems show poor performance in detecting small surface targets, such as small ice pieces in basic event 3 (Islam et al., 2013).

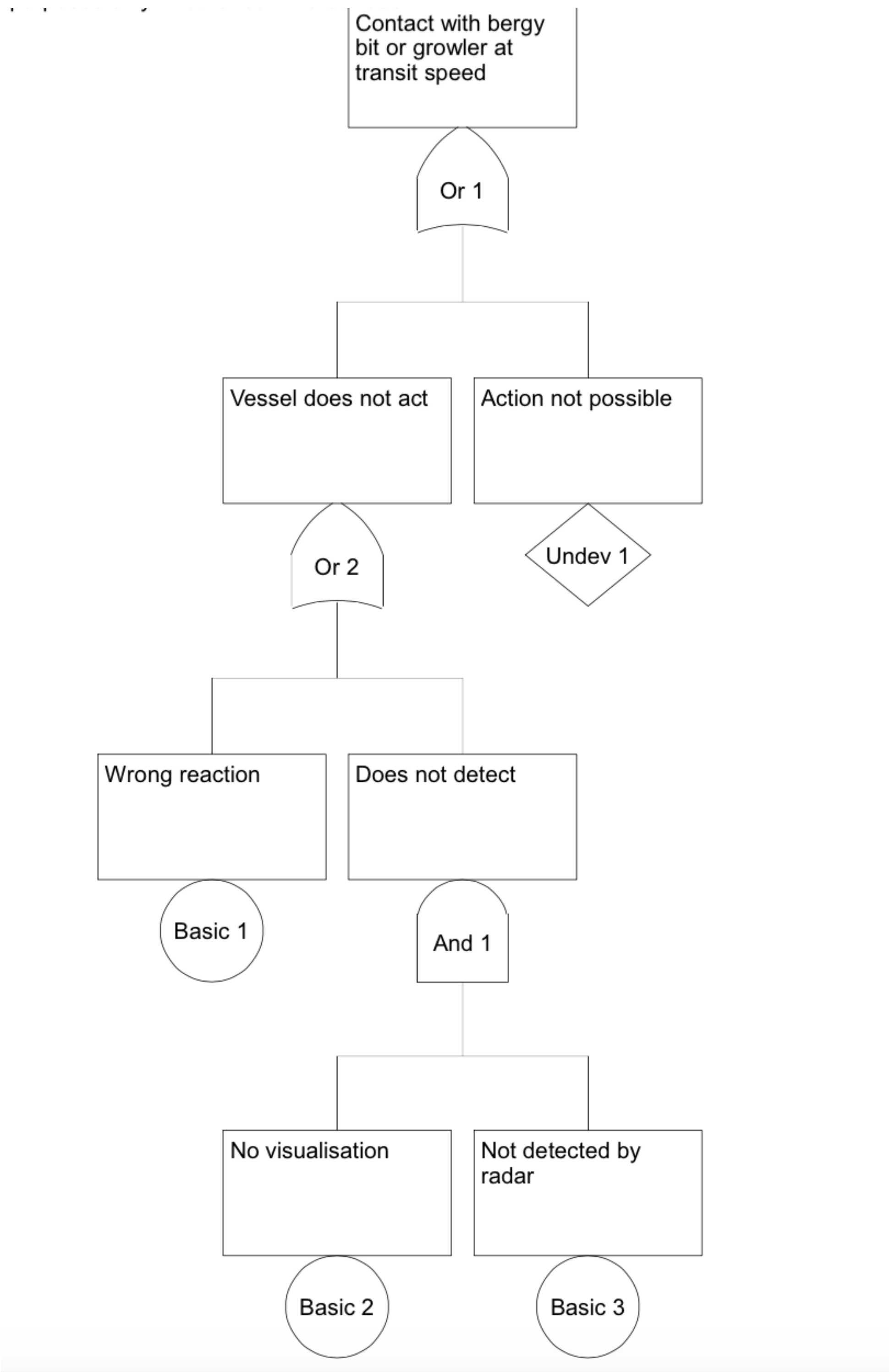

Figure 20: Fault tree diagram

The probability of contact with a bergy bit or growler is estimated using the information from chapter 3. Calving events from icebergs occur periodically, causing a periodical supply of bergy bits and growlers from the parent iceberg. Accidents statistics from 1686 to 2000 give an impact frequency of 0,05732 each year, in the area around Greenland and Newfoundland. These statistics deviate significantly from the statistics from the Arctic Circle from 2005 to 2015, which give a contact frequency of 2 casualties each year.

This is probably due to that many accidents have not been reported during these years, and that the activity in the Arctic area has increased significantly. Another factor for this deviation is that the recent statistics is only categorized as contact and can consider other events than contact with growlers and bergy bits. The amount of contact casualties with bergy bits or growlers is therefore in this analysis estimated to be one third of the total contact casualties.

Cruise tourism is dependent on the contentment of the passenger's experience during the voyage. Arctic cruises are explorer cruises where the passengers are eager to witness wildlife and nature phenomenon unique for the Arctic area. Cruise vessels are therefore often seeking these attractions, where in many cases it involves seeking hazards. For instance, observing an iceberg is interesting for the passengers. By approaching an iceberg the vessel is exposed to hazards related to calving or that the iceberg tips over. The fact that many cruise vessels operate close to the iceberg sources due to the interesting nature is a factor that increases the likelihood of an impact scenario with a cruise vessel. Taking this into the estimation of impact occurrence frequency, and looking at the documented size frequency distribution of calving from icebergs, a figure for frequency can be set to $3{,}6529 \cdot 10^{-4}$ each day, equivalent to an annual frequency of contact to 0,066. Here it is assumed that the casualties have occurred during the summer half of the year and that the vessel is operating in the popular cruise tourism areas, around Svalbard, Franz Josef Land and the coast of Greenland.

5.2 SHIP MODEL FOR PDS CALCULATIONS

As mentioned, the software DELFTShip is used for modelling and calculations on probabilistic damage stability. The hull modelled in the analysis is based on MS Fram, owned and operated by Hurtigruten AS. MS Fram is an explorer cruise ship that is designed for operation in polar waters, and built after the PDS regulations. Hurtigruten AS has provided the general arrangement (GA) to MS Fram for use in the analysis. Due to Hurtigruten AS's privacy the GA cannot be published in this thesis. Specifications for MS Fram are given in table 4.

Table 4: Specifications MS Fram (Sollid, 2015)

Building year	Passenger capacity	Gross Tonnage	Length [m]	Beam [m]	Draught [m]	Speed [kn]	Ice class
2007	318	11 647	124	20,2	5,1	13	1B

When modelling the arrangement for the vessel in the analysis, the focus has been on the arrangement in the forward part, from the baseline to the 2nd deck. This area is considered most exposed to damages caused by drifting ice. The PDS method only considers damages that have a damage extent above the waterline. It is likely that the damages will consider areas under the waterline as well due to the ice formation of growlers and bergy bits, as they have their largest area beneath the water surface. In the analysis, calculations for the attained index A will be done for the arrangement as based on the GA from MS Fram.

Simplifications have been made when modelling the ship in DELFTShip, as unnecessary details have been neglected due to assumed insignificance for the analysis. Figure 21 illustrates the ship model that has been modelled for the case study, while figure 22 illustrates the tank arrangement for below tank top and between tank top and 1st deck. The final model contains 42 damage zones when defining the zones after the compartment boundaries. All tanks have been implemented as it is in the GA from the reference vessel. Other compartments have been modelled as simple compartments, neglecting specific details from the arrangement. The main focus has been to model the watertight compartments as it is in the GA, with particular emphasis on the forward part of the vessel. In addition to simplifications in the model, there are other factors that cause the ship model to deviate from the reference vessel. The hull is not as slender as MS Fram due to difficulties when designing the hull lines. This has been solved by dimensioning the arrangement so the location of the compartments and tanks are located in the same distance from the hull as in the GA.

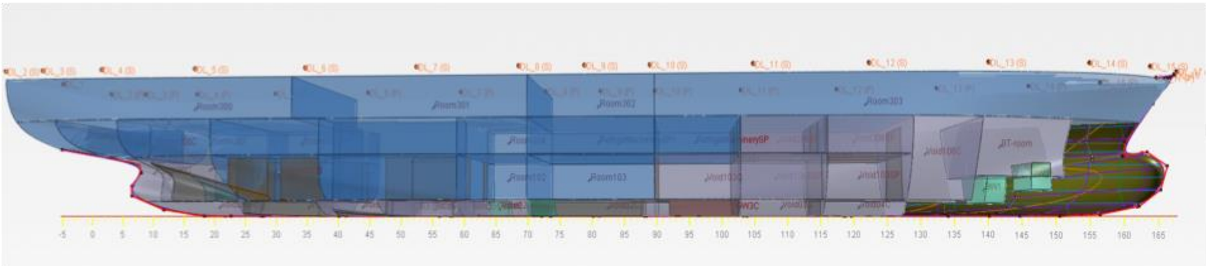

Figure 21: Ship model, DELFTShip

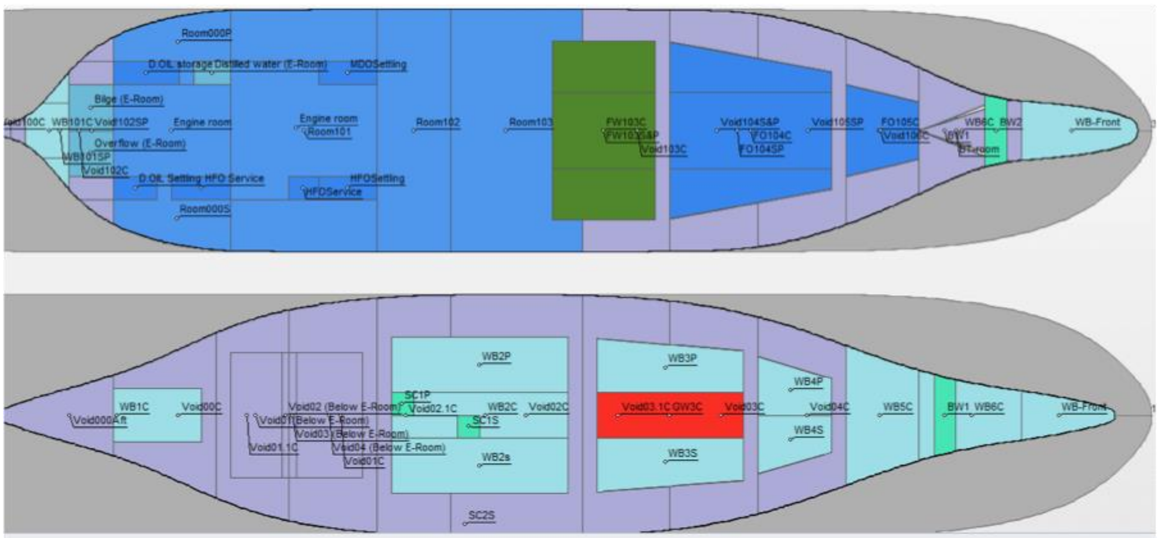

Figure 22: Tank arrangement, below 1st deck and tank top

DELFTShip requires that values for GM for the different draughts considered in PDS to be implemented in order to run the calculations. As mentioned, the ship model is not exactly equal to the reference vessel causing uncertainty regarding the implemented GM values to affect the resulting attained index. The main objective of the analysis is to evaluate the differences in the attained index due to changes in the arrangement. It is therefore difficult to understand to which extent the implementation of the GM values will cause errors in the final results. The values used in the model are based on the values in the reference vessel for the different loading conditions. In order to get a better understanding of the effect of the GM values, analysis is done to verify the results where the GM values are adjusted slightly.

5.3 INITIAL ARRANGEMENT – BENCHMARK OF RISK LEVEL

The ship model and arrangement below tank top and 1st deck is shown in figure 21 and 22 above. Probabilistic damage stability calculations are made on the ship model described. The analysis is performed with GM values 1,8 m for lightest subdivision draught, 1,9 m for partial draught and 2 m for deepest subdivision draught. These values are set based on information given from Hurtigruten AS. The PDS extension in DELFTShip is set to use harmonized stability regulations for passenger vessels implemented from IMO. The results from the PDS calculations from DELFTShip are given in table 5.

Table 5: Attained index, initial arrangement

A: Port Side	A: Starboard Side	Total A
0,82504	0,82455	0,82480

The results from DELFTShip give the attained index on port side, starboard side and a total attained index. As mentioned, measures that cause an increase in A will improve the vessel's capability to stay afloat. This is signified in the increased probability that the time to capsize after an incident has occurred is more than 30 minutes. The remaining probability is the amount of incidents where the time to capsize is less than 30 minutes after the incident has occurred.

An event tree is made based on the event in the fault tree diagram in figure 20. In the event tree in figure 23, a minor incident is considered to cause no or little damage to the ship hull. The vessel can continue the voyage and should be inspected in the next port. Serious casualty is considered to cause a considerable damage to the ship hull, either a significant dent or penetration of the shell leading to flooding of one or several compartments. Flooding is considered to cause the vessel to stay afloat, sink slowly or capsize rapidly. The probabilities are set using a study on the safety level on damaged RoPax ships and information from the stability calculations from DELFTShip (Guarin et al., 2009). The information from the study on the safety level of RoPax vessels is considered to be reasonable to use in this analysis, as MS Fram is built with a large area for storage of cars. This is because MS Fram was originally designed for a different purpose than a cruise vessel, but due to a design flaw it was more suited for cruise vessel operation. The arrangement does therefore have many similarities to RoPax vessels. The attained index from the stability calculations is set as the probability to stay afloat and is taken from the calculations from DELFTShip in table 5.

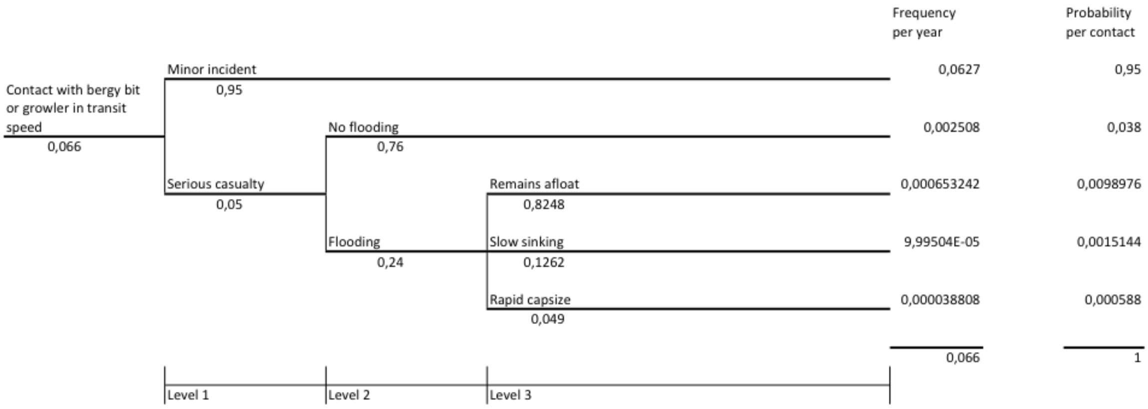

Figure 23: Event tree, initial arrangement

As seen in the event tree in figure 23, the probabilities for slow sinking and rapid capsize is in the ALARP area in the FN curve presented in figure 1, in chapter 3.1. The probabilities are low, but a capsize or sinking of a passenger vessel that carry up to 400 passengers and crew in Arctic waters can imply loss of life of a large number of people. The risk level is therefore in the ALARP region, and risk control options for risk reduction should be considered to increase the capability to stay afloat. Improved damage stability and survivability after flooding is related to the ability to stay afloat, without large heeling angles for as long as necessary making it possible to recover the vessel in case of damage. From the event tree, the probability per contact for remaining afloat is calculated to be 0,0099. It is this probability that is desired to increase with the risk control options, causing a decrease in the probabilities for slow sinking and rapid capsize.

Potential loss of life (PLL) is calculated for this accident scenario where an annual fatality rate is set to 0,5. This estimation is based on the statistics used in the RoPax study where an annual fatality rate is 2 for impact casualties (Guarin et al., 2009). As these statistics yields for all areas, a fatality rate of 0,5 for the Arctic area is assumed reasonable. This estimation gives a PLL of $1{,}826 \cdot 10^{-3}$ using equation 3 in chapter 4.2.5. By comparing with the individual risk criteria presented table 2 in chapter 3.1, the potential loss of life is in the intolerable level. As the calculation of PLL was based on solely reason and assumptions, it cannot be regarded to represent the actual risk level. Ship operation in the Arctic Circle implies a higher overall risk level compared to other oceans due to the possible severity of the consequences if an accident would occur. Thus, the risk should always be mitigated where it is possible for ship operation in Arctic.

5.4 RISK CONTROL OPTIONS (RCOs)

As the risk level for the model analysed in chapter 5.3 is in the ALARP area, measures for risk reduction should be considered. The risk control options are evaluated for improvement of damage stability, i.e. increasing the probability to remain afloat in the event tree in figure 23. After the decision that the risk should be mitigated, different risk control options are usually found by brainstorming technique. The choice of which RCOs that are relevant to assess further, are those that are assumed to be most effective in terms of risk reduction and cost. The aim of studying the effect of implementing the risk control options into the vessel design is to evaluate if implementing is worth doing. In other words, if the ship owner will benefit from the RCO when evaluating both the risk reduction and the cost related to it.

Two options for risk reduction are considered relevant for further evaluation for the accident scenario under consideration. The control options are found by studying the GA to MS Fram, and identifying the weaknesses related to damages from drifting ice. The two RCOs are thoroughly explained in the following sub-chapters. It is important to clarify that the measures are intended for new buildings, thus not to be implemented in already built ships. This is significant when evaluating the cost of implementing the measures.

5.4.1 Risk Control Option I

Risk Control Option I is related to the crew cabins that are located between 1st and 2nd deck in the forward part of the vessel. In case of damage to this area, a hull penetration causing flooding of the crew cabins can result in severe damages. By inserting longitudinal bulkheads from the 1st to the 2nd deck, between shell and crew cabins, it may result in an increase in the attained index by reducing the probability of flooding of the crew cabins. Bulkheads are divisions, or walls, within the ship structure to avoid ingress of water. The bulkheads must be constructed in such a way that it is able to sustain the water pressure in case of flooding. The bulkheads will be located at a distance 800 mm from the shell. This is considered as a sufficient distance, making it possible to perform maintenance and cleaning work. Also, a damage caused by drifting ice is considered likely to not cause penetration above this extent. The resulting flooding will only cover the area between shell and bulkhead, increasing the survivability of the vessel. The measure will have a positive effect on the attained index as the probability of flooding of the crew cabins decrease. The survivability factor S for the damage case will remain the same with a low value, as the compartments are large. As the probability of the damage case decreases, the effect of the low s factor has less influence on the final attained index.

Implementing the RCO will necessitate a movement of the crew cabins towards the centreline. The crew cabins must be located 600 mm closer to the centreline in order to get enough room for the longitudinal bulkheads on each side. This change in location from the initial arrangement reduces the space between the crew cabins on port- and starboard side. In the general arrangement to MS Fram this area is used for a stairwell and a store for crew. A reduction in this space may require a redesign of the arrangement between the crew cabins. It is possible that some of the compartments or systems, such as the store, must be located elsewhere if there is not enough space or the redesign does not comply with the regulations. A change in location for the systems between the crew cabins is not accounted for in the analysis. Figure 24 and 25 show the arrangement before and after the implementation of RCO I. As seen from the figures, the crew cabins have been located closer to the centreline making space for the longitudinal bulkheads. The bulkheads are the added lines between the shell and crew cabins in figure 25. Implementation of bulkheads further forward has not been considered, as it is the crew cabins that are regarded as the critical areas in case of damage due to the potential large area of flooding.

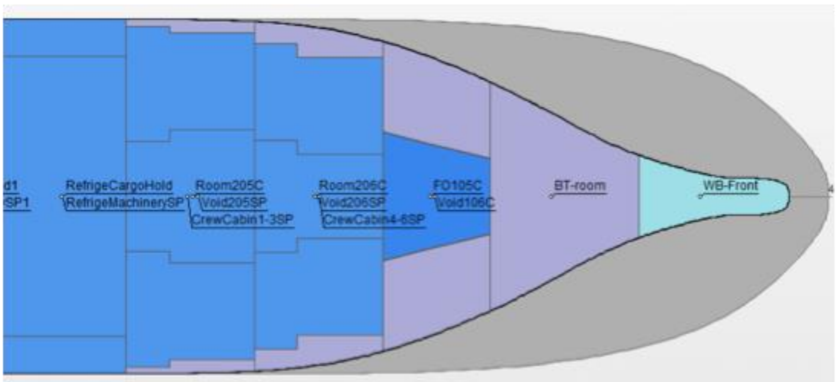

Figure 24: RCO I, before implementation

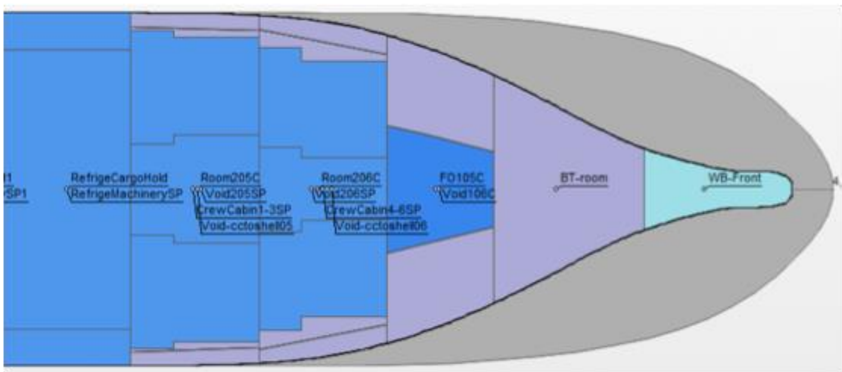

Figure 25: RCO I, after implementation

5.4.2 Risk Control Option II

Risk Control Option II is evaluated with the aim of avoiding unsymmetrical damages below tank top and 1st deck in case of damage. In the current tank arrangement, a number of tanks are designed in the longitudinal direction as seen in figure 22. RCO II contains a change in the design of the tank arrangements so that tanks are designed in the transverse direction. The outer boundaries of the tanks will remain the same thus the new design will not affect on the surrounding arrangement. The implementation of the RCO will ensure symmetrical flooding in case of damage to these areas. This is desired, as unsymmetrical flooding will cause the vessel to heel due to unsymmetrical buoyancy. Heeling of the vessel will make it difficult for crew and passengers to manoeuvre and if the flooding continues, the heeling angle will increase. In case of excessive heeling angles, above 20 degrees, capsize is likely to occur. Measures that ensure symmetrical flooding will increase the survivability of the vessel as it improves the vessel's capability to remain upright in case of damage, thus it will have a positive effect on the attained index. Cross-flooding arrangements for symmetrical flooding should also be considered in the arrangement where it is applicable, but is not considered in the analysis of RCO II.

RCO II considers change in the design of six tanks located below tank top and six tanks located between tank top and 1st deck. The tanks are located from mid-ship to the forward part of the vessel. This area is exposed to damages caused by drifting bergy bits and growlers. The damage extent is likely to cover areas from above the waterline to the baseline as the ice pieces have their largest area below the waterline. Figure 26 shows the implementation of risk control option II. The implementation of RCO II is easily seen by comparing the initial arrangement in figure 22 with the arrangement in figure 26.

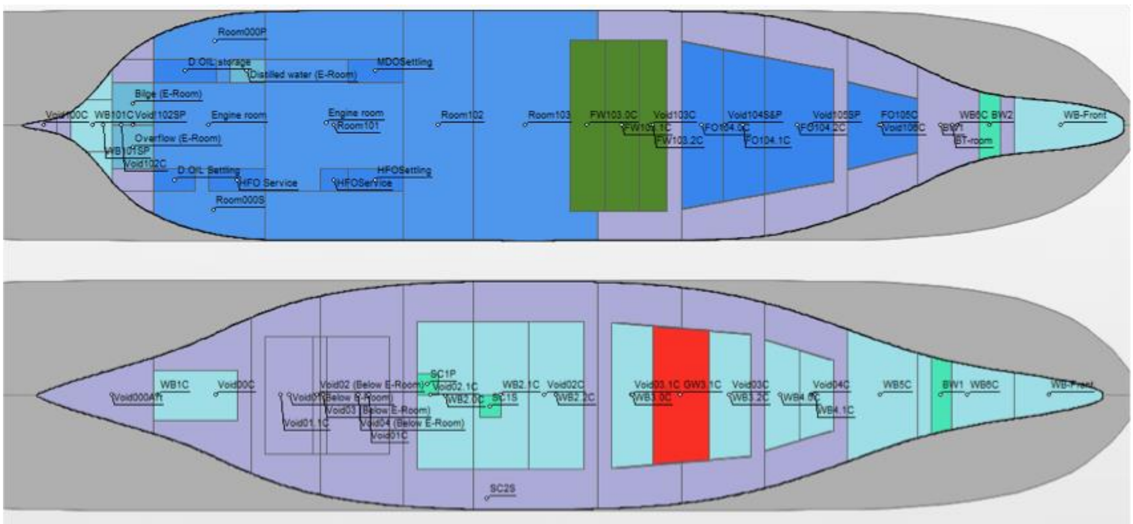

Figure 26: RCO II

5.5 COST BENEFIT ASSESSMENT

In a cost benefit assessment it is necessary to estimate the cost of implementing the risk control options. The costs considered are those related to the design and engineering, and the work on the yard needed for the implementation of the measures in a new-building. Thus, the cost estimations are based on the cost of planning, steelwork, labour and working hours needed for implementation of the measures. The cost approximations made for the two risk control options are based on conversations with co-supervisor, the study on the safety level on damaged RoPax vessels and reasonable assumptions. Table 6 contains costs used in the analysis in US Dollars (USD).

Table 6: Costs used in cost analysis (DMR, 2014) and (Guarin et al., 2009)

Steel price, 2012 [USD/ton]	Price of steel work [USD/ton*h]	Price of planning (consultant rate) [USD/h]
185	6,7	100,5

Calculation of the price of planning and building of the steelwork is done according to equation 24.

$$Total\ cost = Cost\ of\ planning + Cost\ of\ steel\ work + Cost\ of\ steel \qquad Eq.24$$

Where

$$Cost\ of\ planning = Price_{planning}\left[\frac{USD}{h}\right] \cdot Time_{planning}[h]$$

$$Cost\ of\ steel\ work = P_{steelwork}\left[\frac{USD}{ton \cdot h}\right] \cdot Time_{steelwork}[h] \cdot Steel\ [ton]$$

$$Cost\ of\ steel = P_{steel}\left[\frac{USD}{ton}\right] \cdot Steel\ [ton]$$

In addition to the cost of implementation, the implication cost of implementing the risk reducing measures must be considered. Implication costs are costs that arise as a consequence of the measures, such as relocation of systems due to reduced space causing additional work in planning and at the shipyard.

5.5.1 Cost of RCO I

Implementing risk control option I will require hours for planning and steelwork, as well as a small increase in the vessel's lightweight. Additional time for planning is estimated to be 30 hours, including implementation of the design measure in software for stability and different technical drawings and specifications. Time added for steelwork is estimated to be 40 hours in steel preparation and welding operations.

The amount of steel needed for the longitudinal bulkheads can be calculated by the area and thickness of the plating, in addition to the stiffeners needed. The plate thickness should be of 10 mm according to the expected strength needed to sustain the water pressure in case of water ingress. The additional steel weight of the stiffeners is roughly estimated to be 20 % of the plate weight. Thus, the added steel weight by implementing RCO I is calculated to be 7,8 ton, with a steel density of 8,05 ton/m^3. Based on these estimations, the total cost of implementing RCO I is calculated using equation 24 to be 6548 USD. The costs of implementing RCO I is listed in table 7. The implication cost of implementing RCO I is not considered, as it is difficult to set a value due to the uncertainty of the implication. Since the measure is intended for future vessels, the implication cost is assumed to be minor.

Table 7: Cost of implementing RCO I

Cost of planning [USD]	Cost of steelwork [USD]	Cost of steel [USD]	Total cost [USD]
3015	2090	1443	6548

5.5.2 Cost of RCO II

Implementing risk control option II will not require a lot of time for planning and steelwork as the measure does not involve a great deal of differences from the initial design. The amount of steel and time for steelwork are therefore estimated to be the unchanged. Based on these estimations, the total cost will only consider the cost of planning. Time spent for planning of implementing the design change is considered to be 8 hours. Included in these hours are calculations in design and implementation of design in software for stability and different drawings and specifications. The change in design will not affect the surrounding arrangement, as the outer boundaries of the tanks will be the same. It will, however, be necessary to perform calculations and make decisions on locations for divisions of the different tanks. According to the equation 24 and the information in table 6, the total cost of implementing RCO II is 804 USD. The results of the cost of implementing RCO II is listed in table 8. As the measure does not affect the surrounding arrangement, it is assumed that the measure will not cause an implication cost.

Table 8: Cost of implementing RCO II

Cost of planning [USD]	Cost of steelwork [USD]	Cost of steel [USD]	Total cost [USD]
804	-	-	804

As mentioned, the assumptions taken for the cost analysis are rough estimates. The costs are considered to give an indication of the costs of implementing the risk reducing options to be used for further evaluation.

The cost effectiveness of introducing the two risk control options can be calculated based on the estimated costs presented here and the risk reduction of the measures that are presented in chapter 6.

5.6 PDS CALCULATIONS ON AN INDIVIDUAL DAMAGE CASE

Probabilistic damage stability calculations are done on an individual damage case and compared with the results in DELFTShip, in order to verify the reliability of the results from the software. In addition to validating the quality of the results from DELFTShip, it is an effective approach to learn the PDS methodology by seeing how the calculations are done on a simple damage case. The damage case considered is a one-zone damage case. A one-zone damage is a damage that has a damage extent on only one zone on the vessel. The rules in SOLAS Part B-1: Stability that are presented in chapter 4, are used for the calculations.

The ship model used for the example calculations is a different model than the one used in the case study. This is due to the complexity of the model made for the analysis. As mentioned, a difficulty with DELFTShip was that it was not possible to determine the damage zones manually before performing PDS calculations. The zones could only be determined by either the compartment boundaries or tank boundaries, causing the damage zone arrangement to be more complex than what was initially intended. The complexity of the model causes the hand calculations to be extensive. The model that is used for hand calculations is simple in comparison, making the calculations easier. The damage case that is calculated is presented in figure 27.

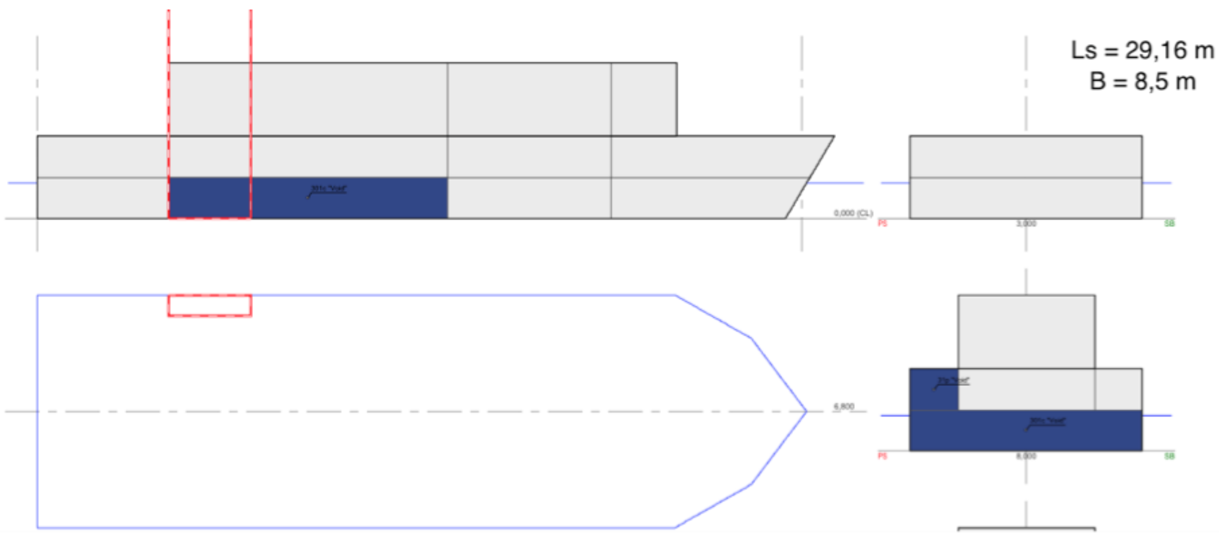

Figure 27: Damage case

PDS calculations are conducted for the specific damage case shown in figure 27. Finally, the attained index can be calculated according to equation 9 for the partial loading condition and compared with the results from DELFTShip.

$$A_C = \sum_{1}^{i=t} P_i S_i V_i \qquad Eq.9$$

5.6.1 Calculation of the P_i factor

The damage is in zone 3, having zone limits x_1 = 15 m and x_2 = 21 m. x_1 is the distance from the aft end of the vessel to the aft end of the zone, and x_2 is the distance from the aft end of the vessel to the forward end of the zone. Dividing the ship into damage zones is done to specify where the damages should be applied and limited. Since the damage case is a one-zone damage, the calculation of the p factor is according to equation 10. As seen in the cross section in figure 27, the damage case is a two-compartment damage.

$$P_i = p(x1_j, x2_j) \cdot \left[r(x1_j, x2_j, b_k) - r(x1_j, x2_j, b_{k-1})\right] \qquad Eq.10$$

The subdivision damage length, L_s, of the vessel is measured to 29,16 m. Since $L_s < L^*$, the formula for J_m is

$$J_m = \min\left(J_{max}, \frac{l_{max}}{L_s}\right)$$

J_{max} is 0,3030, taken from table 3.

$\frac{l_{max}}{L_s} = \frac{60}{29,16} = 2,058$

The least of these values is J_{max}, thus J_m is set to 0,3030.

J_k is calculated by the formula:

$$J_k = \frac{J_m}{2} + \frac{\sqrt{1 + (1 - 2p_k)b_0 J_m + \frac{1}{4}{b_0}^2 {J_m}^2}}{b_0}$$

Where b_o is calculated by the formula:

$$b_0 = 2\left(\frac{p_k}{J_{kn}} - \frac{1 - p_k}{J_{max} - J_{kn}}\right)$$

By using the values for p_k J_{kn} from table 3, b_o is calculated to be 11, and J_k is calculated to be 0,151515.

The normalized damage length, J_n, is found according to the formula:

$$J_n = \min\{J, J_m\}$$

Where J is calculated to be 0,2058 using the formula below with $x_1 = 15$ m and $x_2 = 21$ m:

$$J = \frac{(x2 - x1)}{L_s}$$

J_n is set to 0,2058, since the value is smaller than $J_m = 0{,}3030$.

b_{11}, b_{12}, b_{21} and b_{22} are calculated by using the formulas below to find the non-dimensional damage length. Since $L_s < L^*$, b_{12} is equal to b_0.

$$b_{11} = 4\frac{1 - p_k}{(J_m - J_k)J_k} - 2\frac{p_k}{{J_k}^2} = -65{,}34 \qquad b_{12} = b_0 = 11$$

$$b_{21} = -2\frac{1 - p_k}{(J_m - J_k)^2} = -7{,}26 \qquad b_{22} = -b_{21}J_m = 2{,}2$$

The formula for calculation of $p(x_1, x_2)$ is found by looking at the damage case under consideration. Since the compartments limits do not coincide with any of the aft terminals, i.e. the stern or bow of the vessel, the first approach found in 1.1.1, regulation 7-1 in SOLAS is used, thus using equation 12. Since $J > J_k$, $p(x_1, x_2)$ is calculated to be 0,1395 using the formula for p_2 below:

$$p_2 = -\frac{1}{3}b_{11}{J_k}^3 + \frac{1}{2}(b_{11}J - b_{12}){J_k}^2 + b_{12}JJ_k - \frac{1}{3}b_{21}\left({J_n}^3 - {J_k}^3\right) + \frac{1}{2}(b_{21}J - b_{22})\left({J_n}^2 - {J_k}^2\right) + b_{22}J(J_n - J_k) \qquad Eq. 12$$

For calculation of the r factor, the transverse penetration is considered. The r factor is calculated by equation 15.

$$r(x1, x2, b) = 1 - (1 - C) \cdot \left[1 - \frac{G}{p(x1, x2)}\right] \qquad Eq. 15$$

C is calculated using the formulas below:

$$C = 12 \cdot J_b \cdot (-45 \cdot J_b + 4)$$

$$J_b = \frac{b}{15B}$$

b is the penetration depth for the specific damage case and B is the beam of the vessel. As seen in figure 28, the penetration depth does not exceed the longitudinal bulkhead and b is therefore set to 1,75 m. The r factor for b_{k-1} is not considered as the damage extent does not penetrate any of the longitudinal bulkheads. By implementing the values into the formula, J_b is calculated to be 0,01373. Implemented in the formula for C, C is calculated to be 0,5572.

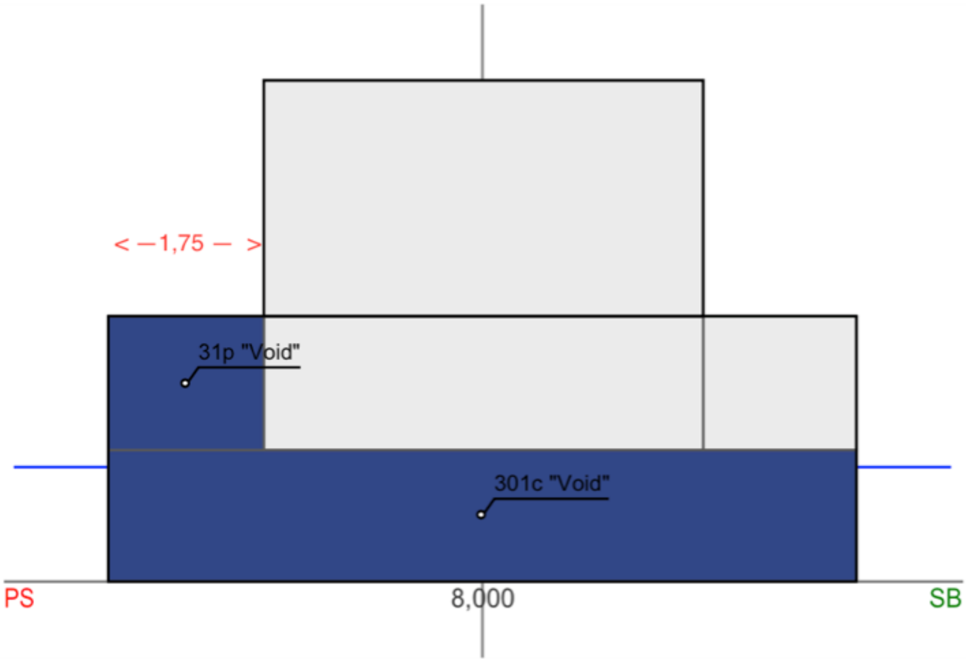

Figure 28: Damage case, transverse section

For calculation of G, the correct approach must be selected. As in the selection of the approach for calculation of $p(x_1, x_2)$, the compartment limits does not coincide with any of the aft terminals on the vessel. The second approach, 1.2.2 in SOLAS regulation 7-1, equation 17, is used.

$$G = G_2 = -\frac{1}{3}b_{11}{J_0}^3 + \frac{1}{2}(b_{11}J - b_{12}){J_0}^2 + Jb_{12}J_0 \qquad Eq.17$$

Where $J_0 = min\{J, J_b\}$. Since J_b is the least value J_0 is set to 0,01373. By implementing the values into the formula for G_2, G is calculated to be 0,027778.

So, by implementing the calculated values for J_b, C and G in equation 12, the r factor is calculated to be 0,6453.

Now the Pi factor for the damage case can be calculated using equation 10, and the P_i factor is calculated to be 0,09052.

5.6.2 Calculation of the S_i factor

Calculation of the survivability factor is dependent on different parameters depending on the type of vessel. The ship model used is a passenger vessel, thus $S_{intermediate}$, S_{final}, and S_{mom} must be calculated. The S_i factor is calculated using equation 19.

$$S_i = min\{S_{intermediate,i}, S_{final,i} \cdot S_{mom,i}\} \qquad Eq.19$$

S_{final} is calculated using equation 20.

$$S_{final} = K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16}\right]^{\frac{1}{4}} \qquad Eq.20$$

The GZ curve for the damage scenario is used to find information regarding GZ_{max}, range and angle of equilibrium. The GZ curve in partial draught for the damage case is shown in figure 29. The curve is taken from the stability report from DELFTShip.

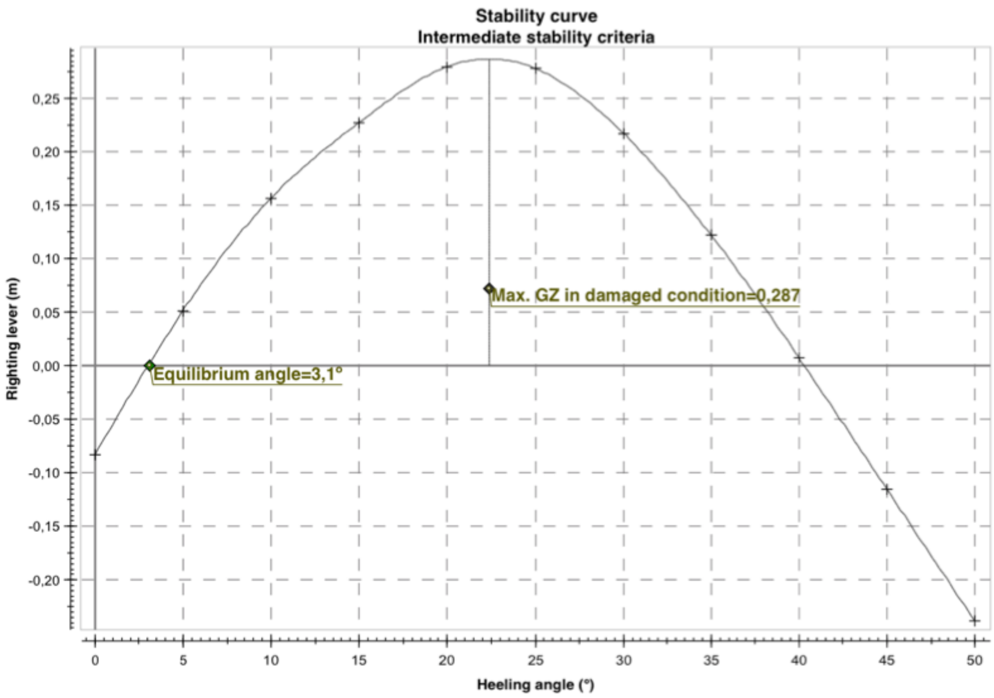

Figure 29: GZ curve for damage case

Equilibrium angle and GZ_{max} are read from the curve. The angel of equilibrium, θ_e, is 3,1 degrees and GZ_{max} is 0,287. Range is the distance in heeling angle between where the curve crosses the x-axis and read of the curve to be 37,2 degrees. K is calculated by the formula:

$$K = \sqrt{\frac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$$

Since θ_e is less than θ_{min} (7 degrees for passenger ships), K is set equal 1. For this damage case, range and GZ_{max} is larger than 16 and 0,12 respectively. These values cannot be larger than the limits, the values are thus set to the limits causing the calculated S_{final} to be 1. This is because the value of S cannot be larger than 1.

$S_{intermediate}$ is calculated using equation 15.

$$S_{intermediate} = \left[\frac{GZ_{max}}{0.05} \cdot \frac{Range}{7}\right]^{\frac{1}{4}} \qquad Eq. 15$$

The calculation of $S_{intermediate}$ necessitates that a GZ curve is plotted for all intermediate stages of flooding. Plotting of all these curves are highly time consuming and is therefore not done for calculation of $S_{intermediate}$. The value is set equal 1, as there is nothing that indicates that the factor will give a lower value than S_{final}.

S_{mom} is calculated using equation 22.

$$S_{mom,i} = \frac{(GZ_{max} - 0.04) \cdot Displacement}{M_{heel}} \qquad Eq. 22$$

M_{heel} is the maximum value of $M_{passenger}$, M_{wind} and $M_{survivalcrafts}$. $M_{passenger}$ is calculated according to the formula:

$$M_{passenger} = (0.075 \cdot N_p) \cdot (0.45 \ \cdot B)$$

N_p is maximum number of passengers permitted and is set to 100 passengers. By implementing in the formula, $M_{passenger}$ is calculated to be 28,679 tm. M_{wind} is calculated according to the formula:

$$M_{wind} = \frac{P \cdot A \cdot Z}{9806}$$

A is the projected wind area, set to 127 m^2, Z is the distance from the projected wind area to half the draught, set to 3,02 m, and P is the force per area, set to 120 N/m^2. Based on this information, M_{wind} is calculated to be 4,693 tm. $M_{survivalcrafts}$ is set to equal 0, as the vessel is not outfitted with survival crafts.

Since $M_{passenger}$ is the maximum of the calculated values for M, M_{heel} is set to 28,679. S_{mom} can now be calculated for the damage case using equation 22 with the value of the displacement in the partial draught loading condition. This value can be found using DELFTShip and is set to 265 ton for the partial draught condition. The calculated value for S_{mom} is 2,28, however the value for S_{mom} should always be less or equal to 1, thus the value for S_{mom} is set to 1.

The S_i factor can now be calculated using equation 19. The values for the different S factors have all been calculated to 1, thus S_i is equal to <u>1</u>.

5.6.3 Calculation of the v_i factor

The v_i factor considers the vertical extent of the damage and is the probability that a deck above the waterline will remain intact. V_i is calculated using equation 23.

$$V_i = v\left(H_{m,d}\right) - v(H_{(m-1),d} \qquad Eq. 23$$

As mentioned in chapter 4.3.6, when calculating the V_i factor, the compartments considered are those damaged and the deck that limits the damage case, located above the waterline. As seen in figure 28, the only deck that must be considered is the deck located 3 m above the baseline. This is the only damaged compartment that is located above the waterline. Figure 28 shows that the height from the baseline to H_1 is 1,5 m and the height to H_2 is 3 m. Draught in the partial draught loading condition is 1,8 m. Therefore, even though the deck H_1 is part of the damage case, it is located below the waterline in the partial draught condition and is therefore not considered in the calculation for V_i. v(H,d) must be calculated for the deck related to the damage case. Before calculating v(H,d), the distance between the height of the deck to the waterline must be calculated in order to find out which approach to use.

$$H - d = 3 - 1{,}5 = 1{,}5$$

Since the distance is lower than 7,8 m, v(H,d) is calculated using the formula:

$$v(H, d) = \ 0.8\ \frac{(H - d)}{7.8}$$

By implementing the values for H and d, the V_i factor for this damage case is calculated to be <u>0,15384</u>.

5.6.4 Calculation of the attained index, A

As P_i, S_i and V_i are calculated for the damage case, these values can be implemented in equation 9 in order to get a value for the attained index. The three factors calculated are summarized in the table 9 as well as the calculated A. Values from the probabilistic damage stability calculations in DELFTShip is listed in table 9 for comparison.

Table 9: Calculations on individual damage case

	P_i	S_i	V_i	A
Calculations	0,0905	1	0,1538	0,01392
DELFTShip	0,0905	1	0,1538	0,01392

Table 9 show that the calculations done by hand give the exact same results as DELFTShip. Based on these results, DELFTShip is considered to give reliable results for the case analysis done in this chapter. However, it must be kept in mind that software is not considered in the maritime industry to be a sufficient tool for damage stability calculations. Also, the ship model considered in this calculation is simple. The model made for the analysis is more complex than the one used for comparison with DELFTShip. It is therefore not given that calculations on the more complex model will give as accurate results as calculated here.

CHAPTER 6

RESULTS

6.1 RESULT OF IMPLEMENTING THE RCOs

The effect of implementing the risk control options are found by implementing the two RCOs in the ship model in DELFTShip. Probabilistic damage stability calculations are performed on the two arrangements where the RCOs are introduced. The difference in the attained index is accounted for by adding the increase in the event tree in figure 23 for the probability of remaining afloat. The resulting change in the event tree will therefore only affect the flooding branch in level three, remain afloat, slow sinking and rapid capsize. The probability of slow sinking and rapid capsize will reduce if the attained index increases as, the sum of the branches in level three must be equal to one. The individual decrease in the probability of slow sinking and rapid capsize are done based on the assumptions that the RCOs will mostly affect the probability of rapid capsize rather than the probability of slow sinking. Based on this the largest decrease is considered in the probability of rapid capsize and a small decrease is considered in the probability of slow sinking.

The results from the implementation of RCO I and RCO II in DELFTShip are presented in the two following sub-chapters.

6.1.1 Result of implementing RCO I

Probabilistic damage stability calculations from DELFTShip after implementing RCO I give an attained index of 0.82935. This is an increase from the initial attained index of 0,56%. In other words, the probability to stay afloat has increased to 82,93% from 82,48%. This gives a slightly improved capability to stay afloat longer, as the share of damages that will have a survival time of at least 30 minutes has increased. The resulting event tree after implementing the longitudinal bulkheads between shell and crew cabins are illustrated in figure 30.

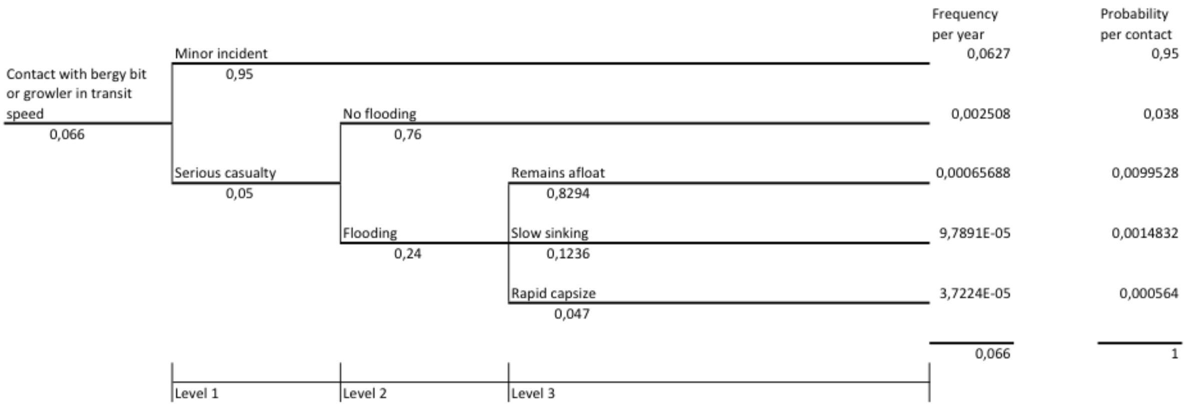

Figure 30: Event tree, RCO I

As seen in figure 30, the branch probabilities in level three has changed slightly as a result of the introducing the RCO I in the ship model. The results of implementing RCO I are listed in table 10. The branch probability considered is the probability per contact.

Table 10: Result RCO I

A	ΔA [%]	Branch probability	Δ Branch probability
0,82935	0,56	0,00995	$5*10^{-5}$

6.1.2 Result of implementing RCO II

The probabilistic damage stability calculations from DELFTShip after implementing RCO II give an attained index of 0,82584. This is an increase from the initial attained index of 0,12%. The probability to stay afloat has increased to 82,58% from 82,48%. This will also cause a slightly improved capability to stay afloat longer, as the share of damages that will have a survival time of at least 30 minutes has increased. The resulting event tree after changing the design of the tank arrangement below tank top and between tank top and 1st deck is illustrated in figure 31.

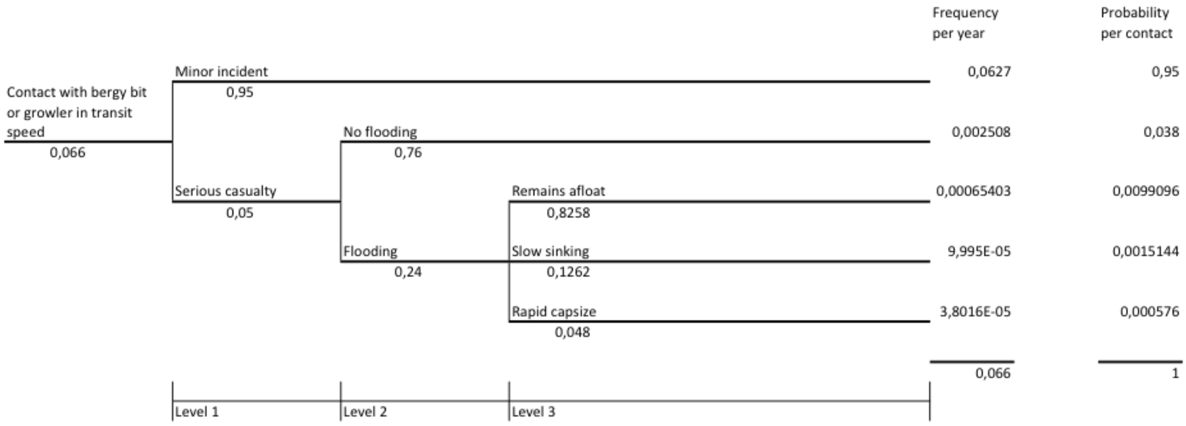

Figure 31: Event tree, RCO II

The event tree in figure 31 presents the results of implementing RCO II in the ship model, where the branch probabilities in level three has improved slightly. The results of implementing RCO I are listed in table 11.

Table 11: Result RCO II

A	ΔA [%]	Branch probability	Δ Branch probability
0,82584	0,12%	0,00991	$1*10^{-5}$

In order to evaluate whether the two RCOs should be recommended, the cost benefit of the risk reducing options must be assessed.

6.2 COST BENEFIT OF IMPLEMENTING THE RCOs

Gross Cost of Adverting a Fatality (GCAF) is used to evaluate whether the measure should be implemented or not. GCAF is the ratio between the cost of implementing the measure and the risk reduction as a result of implementing the measure. It is calculated using equation 2 from chapter 4.2.1.5. As mentioned, the calculated GCAF must be lower than 1,93 million USD based on the willingness to pay in Norway during the recent years.

The risk benefit is set to be the same value as the resulting branch probability per contact has increased by implementation of the RCOs. This is considered to be reasonable as it is the probability of remaining afloat that has been affected by the risk control options.

6.2.1 Cost benefit of RCO I

The cost of implementing RCO I was in chapter 5.4.1 calculated to be approximately 6548 USD. The risk reduction as a result of the increased attained index is found from the event trees. The probability of staying afloat has increased to 0,8294 and accordingly increased the branch probability to 0,00995 from 0.00990. This gives a percentual increase, thus a risk benefit, of $5{,}05 \cdot 10^{-3}$.

By using equation 3 with a cost of 6548 USD and risk benefit of $6{,}06 \cdot 10^{-3}$, the GCAF for RCO I is calculated to be 1,30 million USD. This value is less then the limit for GCAF, and the risk control option can thus be recommended for implementation. The results of the cost benefit assessment of RCO I are listed in table 12.

Table 12: Cost benefit RCO I

Increase in attained index, A [%]	Risk benefit, ΔR	Cost of implementation [USD]	GCAF [USD]
0,56	$5{,}05 \cdot 10^{-3}$	6548	1,30

6.2.2 Cost benefit of RCO II

The cost of implementing RCO II was calculated to be approximately 804 USD. The probability of staying afloat has increased to 0,8258 and accordingly increased the branch probability to 0,00991 from 0,00990. This gives a percentual increase, thus a risk benefit, of $1{,}01 \cdot 10^{-3}$.

By using equation 3 with a cost of 804 USD and a risk benefit of $1{,}01 \cdot 10^{-3}$, the GCAF for RCO II is calculated to be 0,80 million USD. This value is less than the limit for GCAF, and the risk control can thus be recommended for implementation. The results of the cost benefit assessment of RCO II are listed in table 13.

Table 13: Cost benefit RCO II

Increase in attained index, A [%]	Risk benefit, ΔR	Cost of implementation [USD]	GCAF [USD]
0,12	$1{,}01 \cdot 10^{-3}$	804	0,80

6.3 VERIFICATION OF RESULTS BY EVALUATING GM VALUES

Further analyses are performed due to the uncertainty regarding the accuracy of the selection of GM values in the analysis. As mentioned, DELFTShip requires that GM values are implemented in order to run probabilistic damage stability calculations. Due to several inconsistencies between the model designed in DELFTShip and the actual vessel used for reference, there are uncertainties regarding the choice of GM values for the analysis. Hurtigruten As has provided useful information regarding MS Fram, and the choice of GM values are based on this information. To verify if the results are reasonable, further analyses are made where the GM values are increased and decreased slightly to analyse the effect of the GM values. The objective of the analysis is the difference in the attained index due to changes in the arrangement. It is therefore necessary to verify the difference in the attained index between the arrangements when analyses are done with changed GM values.

Analyses are performed with reduced and increased GM values for the lightest service draught, partial draught and deepest subdivision draught. The values for GM in the initial analysis are set to 1,8 m, 1,9 m and 2 m for the different draughts. In the analysis with reduced values for GM, the values are set to 1,6m, 1,7 m and 1,9 m. The values for the analysis with increased GM are set to 2, 2,1 and 2 m respectively. These values are considered relevant based in the information from Hurtigruten AS. The results from the analysis are listed in table 14.

Table 14: Results from GM analysis

	Initial GM values		Reduced GM values		Increased GM values	
	A	**ΔA [%]**	**A**	**ΔA [%]**	**A**	**ΔA [%]**
Initial design	0,82480	-	0,80623	-	0,85454	-
RCO I	0,82935	0,56	0,81438	1,01	0,85895	0,52
RCO II	0,82584	0,12	0,81256	0,76	0,85333	-0,14

The results from the analyses show that for the initial design the attained index is reduced with the reduced GM values, and the attained index is increased with the increased GM values. This coincides with general stability theory as increased GM improves the stability of the vessel as it increases the stiffness of the vessel. In the case with the reduced GM values, both risk control options give an increase in A. The increase is in both cases greater than in the case with the initial values. The increase is especially large for RCO II compared to the initial GM values. The results show that the effects of the RCOs are greater when the overall stability for the vessel is worse.

In the analysis with the increased GM values the difference in attained index in RCO I from the original design is nearly equal compared to the initial analysis, from 0,56% to 0,52%. The attained index for RCO II has however reduced due to the implementation. The index has decreased 0,14 % from the original design. This reduction is difficult to comprehend as the other two analysis on RCO II has led to an increase in A. The reduction is however minor. For the initial arrangement and the arrangement with RCO I, a stiffer boat increase the attained index as a result of the increased GM values. RCO II ensures symmetrical flooding if the tanks located below 1st deck and tank top were to be damaged. The implementation of RCO II will contribute as the vessel has an overall better stability, but then again, this is not the result of the analysis.

In order to understand the decrease in attained index, the zone damages reports from DELFTShip can be used. The zone damage report presents the different possible damages in a diagram as presented in figure 7 in chapter 4.3. The severity of the different damages is distributed by the probability of surviving the damage, from a large likelihood of survival to a low likelihood. The dissimilarities are considered by comparing the report from the initial arrangement with the report from the RCO II arrangement. The damage reports deviate, as the number of damage zones is different in the two arrangements. The different zone numbers are due to that the zone division is based on the compartment boundaries and the compartment arrangement has changed due to the implementation of RCO II. The irregularities in the zone damage reports are mostly for the damages that are considered severe, where the area in the forward part, where the changes are made, has improved, except at the bow where the likelihood of a sever damage has increased. This may be the reason for the decrease in the attained index. The probability of a severe damage has increased due to the implementation of RCO II, causing a negative effect on the final attained index that was clarified when the GM values were increased. The zone damage reports are included in the appendix G.

CHAPTER 7

DISCUSSION

7.1 DISCUSSION OF CASE STUDY

The results from the case study analyses confirm that implementing the risk reducing options proposed will cause a slight increase in the attained index, improving the vessel's capability to stay afloat. However, these results are based on a few analyses where numerous assumptions and simplifications are made.

7.1.1 Discussion of the ship model

The ship model and information used in the analysis are based on Hurtigruten AS's MS Fram. The model made in DELFTShip deviate from the reference vessel in some areas. As mentioned, the model is not as slender as MS Fram. This has been accounted for by increasing the dimensions on the arrangement in the areas where there was a large difference between the model and the general arrangement to the reference vessel. The dimensioning was done to ensure that the distances from the shell to the compartments and tanks were equal to the general arrangement. Another solution could have been to change the hull lines to obtain a hull that resembles better the reference vessel. The drawing received from Hurtigruten AS was solely the general arrangement. To define the vessel's lines just based on this drawing would require extensive amount of time and likely have many uncertainties due to assumptions that would have been necessary to make. Dimensioning the arrangement within the hull was therefore considered to be the best solution. The deviations in the ship model compared to the reference vessel are a source for uncertainty regarding the results, as many parameters have been based on the information on MS Fram.

DELFTShip requires that the GM values for the three loading conditions are implemented in the ship model before performing probabilistic damage stability calculations. The GM values implemented in the model were based on information from Hurtigruten AS. Since the model deviate in some areas from the reference vessel, the uncertainty regarding the implemented GM values can affect the accuracy of the results on the attained index. Without knowing the exact GM values for the ship model, it is difficult to be certain of the results on the probabilistic damage stability calculations.

Analyses where the GM values were increased and decreased showed that for the decreased values the results coincided with the results from the case study analysis, where the effect of the RCOs increase as the overall stability of the vessel is worse. The attained indices from analyses with increased GM values gave different results. For RCO I, the attained index had a similar increase compared to the analyses with the initial GM values. For RCO II however, the attained index decreased slightly. This decrease is difficult to comprehend, as it should have lead to an increase based on the knowledge gained on the probabilistic damage stability method. The comparison of the zone damage reports presented that the probability of a severe damage increased, having a negative effect on the final attained index that was made clear by increasing the GM values. This decrease in the attained index should be evaluated further before deciding to implement the measure to find out whether the RCO actually increase the likelihood of a severe damage in the bow area. However, in the analysis on the modification of the GM values, the draughts were held constant. This is a source of uncertainty of the results as the GM values can have an influence on the draught. The results from the verification analyses of the GM values verify that the GM values are of significant importance for accurate results when doing calculations on probabilistic damage stability. As the effect of the RCOs increased with the decreased GM values, i.e. with the overall worse stability, it can be interpreted that the RCOs will give an increased attained index by implementation.

DELFTShip does not offer the possibility of establishing the layout for the damage zones by own choice. The distribution of damage zones is based on either the compartment boundaries or the tank boundaries. This causes the model to have a large number of damage zones that must be considered for probabilistic damage stability calculations. The damage stability calculations are becoming more complex than what is considered necessary. As the tanks and compartments are changed by the implementation of the RCOs, the number of damage zones is different for the three arrangements. This renders it difficult to perform a more thorough comparison of the arrangements as the damage zones reports are changed. The example calculations in chapter 5.6 were performed on a different ship model as a result of the complexity of the damage zones. Therefore, calculations to verify the accuracy of the results received from DELFTShip were not analysed based on the model used in the analysis. A simpler model was used for probabilistic damage stability calculations and the results coincided with the results from DELFTShip. Thus, a verification of the accuracy of the PDS calculations from DELFTShip of the main ship model used has not been performed. This verification should be performed, as the software is not considered as a sufficient tool for probabilistic damage stability calculations in the maritime industry. This issue add an additional source for uncertainty regarding the results. However, as the purpose of the case study was to evaluate the differences in the attained index from the three arrangements, DELFTShip may be considered to give sufficiently reliable results for the intention of the analysis. This can be assumed since the unreliable issues with the software will affect all the arrangements that are analysed, thus the results on the differences between the arrangements can be considered to coincide with the real scenario.

An additional source for flaws in the analyses is that the ship model is made with little experience within ship design. It is possible that choices have been made in the ship model that does not comply with the regulations. As the focus of the analyses is changes in the arrangement in the forward area of the vessel, this has been the area with more detailed modelling. Leaving the remaining arrangement of the model without much concern can affect the resulting attained index, since the method considers the whole ship model in the probabilistic damage stability calculations. As the objective of the analyses is to evaluate the difference in the arrangement, these simplifications are assumed to not affect the results.

7.1.2 Discussion of risk analysis

The estimation on the frequency of cruise vessel impact with a bergy bit or growler was done based on gathered accident statistics on contact casualties in the Arctic area during the recent years. The statistics did not specify on what types of contact accidents that has occurred, so it has been assumed that one third of the casualties was related to impact with growlers and bergy bits. The locations of the casualties are also not specified in the accident statistics, thus the statistics apply to all areas within the Arctic Circle. The statistics has been presumed to correspond for the locations around Svalbard, Franz Josef's land and the coast of Greenland. As the frequency estimation is not used in the further analysis, the results in the analysis are not affected. The statistics and estimations are considered in the analysis to verify the importance of the issues in this thesis, as the estimation demonstrates that the scenario is likely to occur.

The branch probabilities in the event tree is estimated based on the data used in the study of safety level of damaged RoPax vessels. Since the reference vessel is designed with an arrangement similar to RoPax vessels, the use of the branch probabilities from the RoPax study is considered to be reasonable. However, the RoPax vessels considered in the study are larger than MS Fram. As the arrangement for the vessels used in the study are not presented in the report, it is difficult to estimate whether the arrangements coincide with the arrangement to MS Fram, and accordingly whether the branch probabilities coincide. The branch probability for a serious casualty has been reduced as it was assumed that a serious casualty from an impact with drifting ice is likely to have less severe consequences than an impact with, for instance, a fixed structure. The probabilities in the event tree do not affect the result on the attained index that is used in the rest of the analysis.

The estimations on frequency of impact and branch probabilities on the consequences do not affect the results from the probabilistic damage stability calculations and the cost benefit assessment. The uncertainties regarding the assumptions made in the risk modelling are therefore disregarded.

7.1.3 Discussion of results

The analyses for cost benefit assessment of the two risk control options resulted in that both of the options were cost effective and should therefore be recommended for implementation. The cost estimations are rough estimates based on discussions with co-supervisor, a study on the safety level on a damaged RoPax vessel and reasoning. The cost of implementing the risk control measures can deviate from the results in the analysis, thus further analysis should be performed with more accurate data to ensure that the measures are cost effective. RCO I is more expensive to implement than RCO II, and give a greater increase in the attained index. The implementation of RCO I necessitates that the crew cabins are located closer to the centreline of the vessel. This change reduces the space between the crew cabins on port and starboard side. The consequence of the reduced space has not been accounted for in the analysis and can entail large additional costs that will affect the cost effectiveness of the measure. RCO II does not require additional steel and steelwork, as well as the surrounding arrangement is not affected by the application of the measure. Thus the implementation of RCO II is considered to be at a reasonable price as the only increase is due to some additional design and engineering. It must be kept in mind that the analysis where the GM values were increased resulted in a decrease in the attained index for RCO II. This decrease must be considered for further analyses. It is, however, assumed that the measure will cause a slight increase in the attained index as the measure ensures symmetrical flooding if this area were to be damaged.

The results on the attained indices show just a slight increase from the initial arrangement. However, the measures considered bring minor changes in the arrangement compared to the remaining systems on the vessel. Thus, a greater increase in the attained index can maybe not be expected. The probabilistic damage stability method is based on accident statistics on ship-ship collisions, and does not consider statistics on damages caused by drifting ice in Arctic waters. The results on the attained index can therefore not be considered as completely accurate for the specific accident scenario analysed in the case study. It can, however, be justified by assuming that the resulting difference in the attained index could be greater if the methodology were region based, using statistics on casualties in Polar waters. Based on this assumption, the real effect of implementing RCO I and RCO II would make an even greater increase in the attained index.

The results from the case analyses are based on the information received from Hurtigruten AS and available literature concerning the subject. The information regarding MS Fram should be more detailed, enabling the ship model to better resemble the reference vessel for more accurate results. The results are developed from rough estimations, where the results show just a slight increase in the attained index, with increase at 10^{-3} decimal level. As the results are affected by the assumptions made in DELFTShip, and the increase in the attained index is so minor, the results cannot be considered to be completely reliable. The objective of the analyses was to evaluate the difference in the attained index as a result of the implemented RCOs. As the same assumptions are used for all three analyses, it can be assumed that the differences in the attained index are valid for further evaluation.

To summarize, there are numerous factors that cause sources for uncertainty regarding the results on the attained indices from the case study. The results are assumed to give an indication of the effect of implementing the risk reducing measures for improved damage stability.

7.2 DISCUSSION OF METHOD

Probabilistic damage stability has been used to evaluate safety measures for cruise vessel operation in Arctic waters. As mentioned, probabilistic damage stability is based on accident statistics on ship-ship collisions. The damages caused by impact with drifting ice are different than damages caused by collisions between two vessels. The damages caused by impact with drifting ice are considered to mainly occur in the forward part of the vessel up to the vessel's shoulder, the beamiest point in the forward area. In a ship-ship collision scenario, the bow is the area most exposed for the striking vessel, while the entire vessel is exposed for the struck vessel, and it is the struck vessel that suffers the most damage. Where the arbitrary vessel hits the struck vessel depends on the situation. In head-on collision scenarios, the damage is often located in the forward part of the struck vessel, similar to the accident scenario considered. The inconsistencies on the location of damage affects the p(x1, x2) factor in the probabilistic damage stability calculations. In addition to deviations on the location of the damage, there are deviations regarding the damage extent. In ship-ship collision scenarios, the transverse extent of damage is often large in comparison with damages caused by impact with growlers and bergy bits. This is due to the fact that in ship-ship collisions, the vessel speed, large mass of the striking vessel and the strengthened bow cause large forces during impact between the two vessels. The impact force in a collision scenario is significantly higher than the impact force in an impact scenario with drifting ice in the growler and bergy bit size range. Thus, the penetration extent in transverse the direction is smaller in the accident scenario considered in this thesis, compared to the statistics that probabilistic damage stability are based on. This cause deviations regarding the r factor. The deviations in the p(x1,x2) and r factors affects the P factor in the probabilistic damage stability calculations.

The accident scenario deviates from the statistics in the vertical direction as well. The damage extent in vertical direction on the struck vessel does, in ship-ship collisions, usually cover larger areas above the waterline compared to the damage extent caused by impact with drifting ice. The damage extent as a result of impact with drifting ice is near the waterline. A bergy bit can have a size up to five meters above the water surface, with a large area beneath the waterline. Based on this, the vertical extent of damage above the waterline is maximum five meters, and in most cases less. Since probabilistic damage stability only considers damages above the waterline, a large part of the damage caused by the growler or bergy bit is not included in the methodology. This deviation in the vertical extent of damage causes uncertainty regarding the V factor, and consequently the S factor.

Based on these deviations from the accidents statistics that the probabilistic damage stability method is based on, the results on the attained index cannot be considered to coincide with the accident scenario analysed in this study. It can, however, be assumed that the resulting attained index and the difference in attained index of the implemented RCOs could be even greater if the methodology included statistics on the accidents related to drifting ice. This is a bold assumption that should be analysed further before taking any conclusions.

Probabilistic damage stability is based on accident statistics from all regions. The risk picture differs depending on the area the vessel operates in and on which type of operation the vessel performs. A solution is that the probabilistic damage stability regulations were developed based on region-based statistics and on the type of operation the vessel will perform. This way the vessels can be optimized with regards to safety for the type of operation and location of area the vessel will operate in. This solution would, however, require extensive work in order to acquire sufficient information for the development of reliable probabilistic approaches on different accident scenarios relevant for the type of vessel and operation. Thus, such a development is not a realistic development in the maritime industry in the years to come.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

8.1 SUMMARY AND CONCLUSIONS

On the basis of the work presented in this thesis aimed at reducing the risk of cruise vessel operation in Arctic waters, measures has been found to improve the damage stability and survivability of the vessel. This is based on the assumption that the damaged ship stability is sufficiently reflected by the attained subdivision index, A.

A study on the risk of cruise vessel operation in the areas around Svalbard, Franz Josef land and Greenland show that the vessels operating in these popular cruise tourism areas are exposed for areas with high density of drifting ice pieces, such as growlers and bergy bits. An impact with a growler or bergy bit in transit speed can induce high loads on the ship hull. Depending on the vessel speed and size of the ice piece, there is a risk of shell penetration and succeeding water ingress. As a response to the desire of the vessels to function as ''it's own lifeboat'', measures for improved damage stability has been considered. The risk reduction options evaluated are based on the arrangement of the reference vessel, MS Fram. Risk reduction option I considers implementation of longitudinal bulkheads in the forward area of the vessel, between the shell and crew cabins located between 1st and 2nd deck. A part of this area is located beneath the waterline on the vessel, and is therefore exposed for damages caused by impact with drifting ice. Risk reduction option II considers changes in the tank arrangement for symmetrical flooding. The tanks located below tank top and below 1st deck are changed from heading in the longitudinal direction to the transverse direction. In case of damages to this area, implementation of RCO II ensures symmetrical flooding to improve the vessel's capability to remain afloat.

The results from the probabilistic damage stability calculations from DELFTShip show a slight increase in the attained index for both risk control options. This slight increased index improves the vessel's survivability by increasing the amount of damages where the time to capsize is longer than 30 minutes. Cost benefit assessment on the risk control options show that both RCO I and RCO II are cost effective and can thus be recommended for implementation. The analyses are done based on numerous assumptions causing uncertainty regarding the accuracy of the results. The probabilistic damage stability approach is not based on accidents statistics relevant for the accident scenario considered in the thesis. The probabilistic stability calculations can therefor not be expected to give reliable results. It can, however, be considered to give an indication on the effect of implementing the measures. Based on the results of the analyses, it is demonstrated that the measures for risk reduction can improve the damage stability of the vessel for cruise ship operation in Arctic.

The case study in the thesis show that the scenario addressed is a likely scenario when operating in the popular cruise tourism areas in Arctic. As the interest for the area increases, it is necessary to investigate measures for risk reduction. The accidents described in chapter 3 demonstrate that human behaviour cannot always be reliable in a situation where it is required. It is therefore essential to ensure the safety of passengers and crew in areas that are not dependent on the human performance. Measures for improved survivability after damage are a solution that can prevent emergency evacuation. This is highly desired in the maritime industry, especially for operation in Arctic waters where the remoteness of area can result in many hours waiting time for search and rescue operations.

Thorough explanation of the probabilistic damage stability concept with example calculations are done to give the reader a broad understanding of the approach, in order to follow the progress in the analysis. As mentioned, there are considerable uncertainties regarding the analyses done in this thesis. On the basis of probabilistic damage stability calculations and cost benefit analyses, the measures introduced are anticipated to improve the vessel's capability to remain afloat after suffered damages from drifting ice.

8.2 RECOMMENDATIONS FOR FURTHER WORK

The issues that this thesis addresses are necessary to consider for future operation in Arctic in order to ensure the safety of passengers and crew. The results from the case study show that the risk control measures considered give a slight increase in the attained index. The results cannot be assumed to be entirely reliable due to the uncertainties regarding the ship model and use of the probabilistic damage stability method.

For further analyses, more information must be gathered regarding the reference vessel in order to make the ship model as similar as possible. This is especially important for the GM values implemented in the model, ensuring that the values coincide with the reference vessel to get reliable results. The effect of increased and decreased GM values should be analysed further, evaluating the effect the change has on the different damage cases. Which damage cases, what factor it affects and to what extent should be identified by using the zone damage reports. The uncertainty regarding RCO II that appeared by increasing the GM values must be analysed further before any decisions on implementation can be made. The decrease in the attained index may be a result of that the probability of a severe damage in the bow area increased as a result of implementing the measure. If this is the case, changes on the implementation of RCO II must be considered to ensure that the probability of the severe damage mentioned is not increased.

If possible, the software NAPA should be considered as an alternative to DELFTShip as NAPA is respected as more reliable software for stability calculations within ship design. If further analyses are to be done on the basis of the work addressed in this thesis, the approach of probabilistic damage stability calculations must be altered to fit the accident scenarios relevant for operation in Arctic. Monte Carlo simulations can be used in combination with damage statistics on damages due to ice loads for a more realistic attained index. This will require extensive work on acquiring data on accidents in Arctic to obtain probability density functions for damages due to impact with drifting ice. As the activity in Arctic increases, this can be a solution for risk mitigation.

Also, other cruise vessels operating in Arctic can be evaluated based on the watertight arrangement for the development of risk reducing measures. By evaluating various vessels, risk control options for improved damage stability can be developed as standardized solutions to increase the overall safety level on future vessels.

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APPENDIX

A. DESCRIPTION OF THESIS

NTNU
Norwegian University of Science and Technology

Faculty of Engineering Science and Technology
Department of Marine Technology

MASTER THESIS
Spring 2015

For

M.Sc. student Ragnhild Farstad Høvik
Department of Marine Technology

Application of Probabilistic Damage Stability for Risk Reduction Related to Cruise Ship Operation in Arctic
- A Risk Based Approach

Background

During the recent years the maritime activity in Arctic has increased due to the diminishing ice levels and exploration of resources. The reduced ice levels have made the area more accessible than before, causing an increase in the cruise tourism activity in the Arctic region. The majority of the cruise activities occur in the ice-free waters during the summer months, in the area near Franz Josef's Land, Svalbard and Greenland. These areas are exposed for calving of icebergs and the succeeding calving of growlers and bergy bits. These smaller ice pieces poses threats for vessels operating in the area, as they are hard to detect. An impact scenario with a cruise vessel in transit speed can have severe consequences due to the low temperatures and remoteness of area. This necessitates measures for improved damage stability, increasing the vessel's capability to stay a float in case of damage

Objective

The objective of the master thesis is to evaluate measures in the vessel design to reduce risk for ship operation in Arctic by using risk analysis and probabilistic damage stability (PDS). Different arrangements for improved damage stability will be developed based on studying the arrangement of a cruise vessel used for operation in Arctic, and identifying the weaknesses related to damages caused by drifting ice.

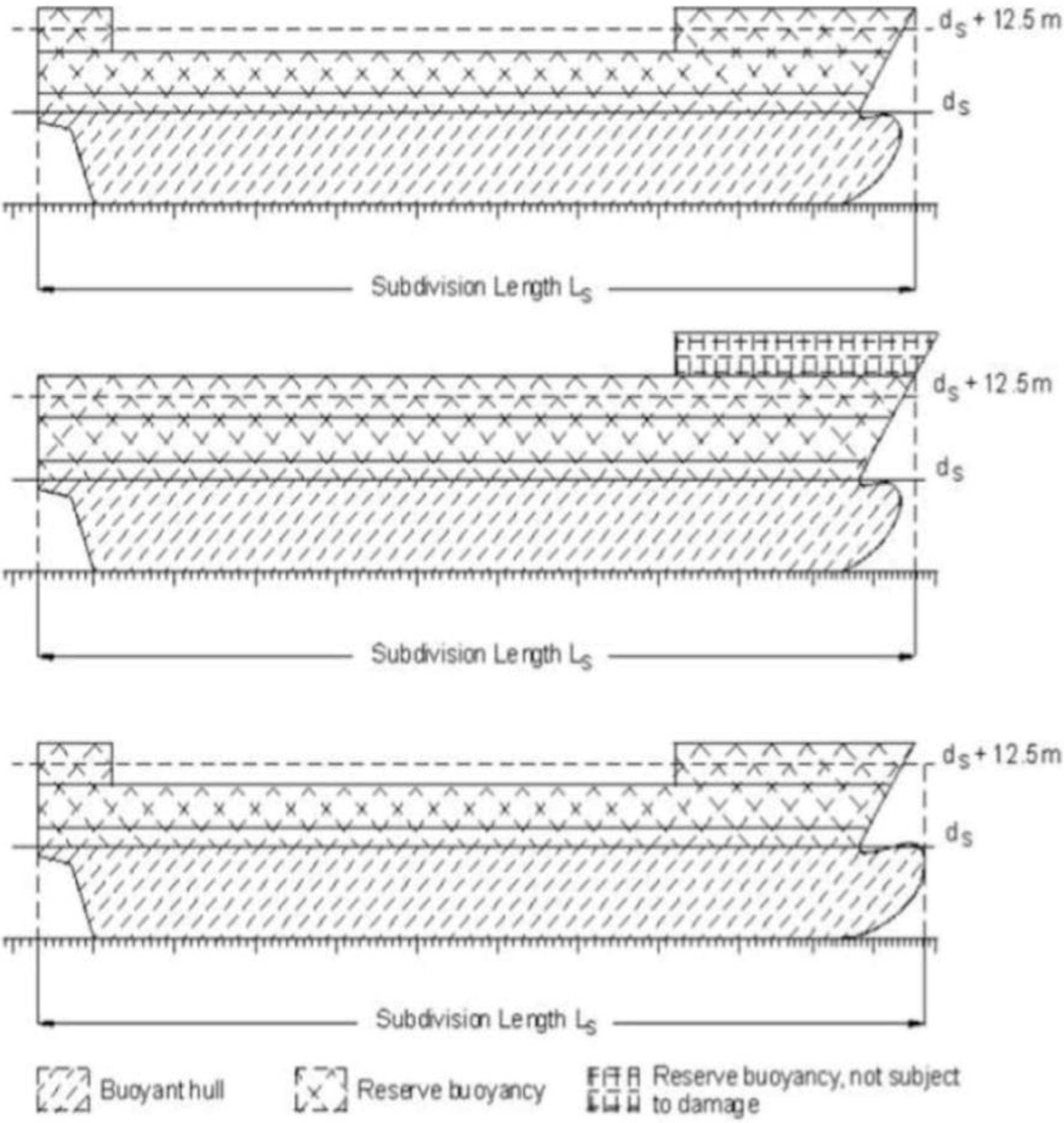
More specifically, the objectives are to:

1) Perform a literature study and on the basis of this study describe:
    a. Methods for stability calculations and the foundation for probabilistic damage stability.
    b. Thorough review of the rules and regulations for PDS for passenger ships.
    c. Risks related to Arctic operation and evaluation of areas with increased risk for damages to the hull due to ice loads.
2) Collection of data
    a. Statistics on ship accidents in Arctic waters and risk acceptance criteria.
    b. Icebergs and drifting ice. Drifting pattern and loads related to impact with vessels.
3) Perform a risk assessment of cruise ship operation in Arctic waters:
    a. Risk acceptance criteria.
    b. Evaluate the consequences of an impact and develop risk control options.
    c. Make a ship model in DELFTShip for PDS calculations.
    d. Implement measures in arrangement and evaluate using PDS. Study difference in attained index and affect of GM value.
    e. Propose best alternative using cost benefit assessment.
    f. Discussion of results.
    g. Conclusions and recommendations for further work.

The thesis shall be written as a research report. During preparation of the thesis, it is important the candidate emphasize easily understood in a well-written text. For ease of reading, the report should include adequate references at appropriate places related to text, tables and figures.

Starting date: 15 January 2015
Completion date: 10 June 2015

B. SUBDIVISION LENGTH Ls



C. RESULTS ON DAMAGE CASE FROM DELFTSHIP

Results of the calculation

Results for: Port side

Damage case		Light service draft				Partial draft				Deepest subdivision draft			
	Pi*Ri	Vi	Pi*Ri*Vi	Si	Ai	Vi	Pi*Ri*Vi	Si	Ai	Vi	Pi*Ri*Vi	Si	Ai
P1.1.1	0,1325	0,0513	0,0068	1,0000	**0,00680**	0,0328	0,0044	1,0000	**0,00435**	0,0205	0,0027	1,0000	**0,00272**
P1.1.2	0,1325	0,9487	0,1257	1,0000	**0,12575**	0,9672	0,1282	1,0000	**0,12819**	0,9795	0,1298	1,0000	**0,12982**
P2.1.1	0,1794	0,0513	0,0092	**0,1560**	**0,00143**	0,0328	0,0059	1,0000	**0,00589**	0,0205	0,0037	1,0000	**0,00368**
P2.1.2	0,1794	0,1538	0,0276	**0,0000**	**0,00000**	0,1538	0,0276	1,0000	**0,02759**	0,1538	0,0276	1,0000	**0,02759**
P2.1.3	0,1794	0,7949	0,1426	**0,0000**	**0,00000**	0,8133	0,1459	1,0000	**0,14588**	0,8256	0,1481	1,0000	**0,14808**
P2.2.1	0,1031	0,0513	0,0053	**0,1560**	**0,00082**	0,0328	0,0034	1,0000	**0,00338**	0,0205	0,0021	1,0000	**0,00211**
P2.2.2	0,1031	0,1538	0,0159	**0,0000**	**0,00000**	0,1538	0,0159	**0,0000**	**0,00000**	0,1538	0,0159	1,0000	**0,01586**
P2.2.3	0,1031	0,7949	0,0819	**0,0000**	**0,00000**	0,8133	0,0839	**0,0000**	**0,00000**	0,8256	0,0851	1,0000	**0,08512**
P3.1.1	0,0905	0,0513	0,0046	1,0000	**0,00464**	0,0328	0,0030	1,0000	**0,00297**	0,0205	0,0019	1,0000	**0,00186**
P3.1.2	0,0905	0,1538	0,0139	1,0000	**0,01392**	0,1538	0,0139	1,0000	**0,01392**	0,1538	0,0139	1,0000	**0,01392**
P3.1.3	0,0905	0,7949	0,0719	1,0000	**0,07193**	0,8133	0,0736	1,0000	**0,07361**	0,8256	0,0747	1,0000	**0,07472**
P3.2.1	0,0490	0,0513	0,0025	1,0000	**0,00251**	0,0328	0,0016	1,0000	**0,00161**	0,0205	0,0010	1,0000	**0,00101**
P3.2.2	0,0490	0,1538	0,0075	1,0000	**0,00754**	0,1538	0,0075	1,0000	**0,00754**	0,1538	0,0075	1,0000	**0,00754**
P3.2.3	0,0490	0,7949	0,0390	1,0000	**0,03898**	0,8133	0,0399	1,0000	**0,03988**	0,8256	0,0405	1,0000	**0,04049**
P4.1.1	0,0222	0,0513	0,0011	1,0000	**0,00114**	0,0328	0,0007	1,0000	**0,00073**	0,0205	0,0005	1,0000	**0,00046**
P4.1.2	0,0222	0,1538	0,0034	1,0000	**0,00342**	0,1538	0,0034	1,0000	**0,00342**	0,1538	0,0034	1,0000	**0,00342**
P4.1.3	0,0222	0,7949	0,0177	1,0000	**0,01766**	0,8133	0,0181	1,0000	**0,01807**	0,8256	0,0183	1,0000	**0,01834**
P4.2.1	0,0090	0,0513	0,0005	1,0000	**0,00046**	0,0328	0,0003	1,0000	**0,00029**	0,0205	0,0002	1,0000	**0,00018**
P4.2.2	0,0090	0,1538	0,0014	1,0000	**0,00138**	0,1538	0,0014	1,0000	**0,00138**	0,1538	0,0014	1,0000	**0,00138**
P4.2.3	0,0090	0,7949	0,0071	1,0000	**0,00713**	0,8133	0,0073	1,0000	**0,00729**	0,8256	0,0074	1,0000	**0,00740**
P5.1.1	0,1027	0,0513	0,0053	1,0000	**0,00527**	0,0328	0,0034	1,0000	**0,00337**	0,0205	0,0021	1,0000	**0,00211**
P5.1.2	0,1027	0,9487	0,0974	1,0000	**0,09744**	0,9672	0,0993	1,0000	**0,09933**	0,9795	0,1006	1,0000	**0,10060**
P6.1.1	0,0177	1,0000	0,0177	1,0000	**0,01768**	1,0000	0,0177	1,0000	**0,01768**	1,0000	0,0177	1,0000	**0,01768**
P1-2.1.1	0,0371	0,0513	0,0019	**0,7683**	**0,00146**	0,0328	0,0012	1,0000	**0,00122**	0,0205	0,0008	1,0000	**0,00076**
P1-2.2.1	0,0287	0,0513	0,0015	**0,7683**	**0,00113**	0,0328	0,0009	1,0000	**0,00094**	0,0205	0,0006	1,0000	**0,00059**
P2-3.1.1	0,0373	0,0513	0,0019	**0,9016**	**0,00173**	0,0328	0,0012	1,0000	**0,00123**	0,0205	0,0008	1,0000	**0,00077**
P2-3.1.2	0,0373	0,1538	0,0057	0,0000	**0,00000**	0,1538	0,0057	**0,0000**	**0,00000**	0,1538	0,0057	1,0000	**0,00574**

D. PDS REPORTS

D.1 INITIAL ARRANGEMENT

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data	Draft (m)	Trim (m)	Displacement (tonnes)	VCG (m)	GM (m)
Light service draft	4,900	0,000	6710,91	8,398	1,800
Partial draft	5,020	0,000	6913,67	8,225	1,900
Deepest subdivision draft	5,100	0,000	7049,99	8,079	2,000

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation	Port side	Starboard side	Required index R
Light service draft	0,82808	0,82598	0,62444
Partial draft	0,82433	0,82408	0,62444
Deepest subdivision draft	0,82424	0,82432	0,62444
Attained index A	0,82504	0,82455	
Required index R		0,69383	
Total attained index		0,82480	

D.2 RCO I

Probabilistic damage stability report

DELFTSHIP Marine Software

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data

	Draft	Trim	Displacement	VCG	GM
	(m)	(m)	(tonnes)	(m)	(m)
Light service draft	4,900	0,000	6710,91	8,398	1,800
Partial draft	5,020	0,000	6913,67	8,225	1,900
Deepest subdivision draft	5,100	0,000	7049,99	8,079	2,000

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation

	Port side	Starboard side	Required index R
Light service draft	0,83044	0,82832	0,62444
Partial draft	0,82846	0,82820	0,62444
Deepest subdivision draft	0,83038	0,83033	0,62444
Attained index A	**0,82962**	**0,82908**	
Required index R		**0,69383**	
Total attained index		**0,82935**	

D.3 RCO II

Probabilistic damage stability report

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data					
	Draft (m)	Trim (m)	Displacement (tonnes)	VCG (m)	GM (m)
Light service draft	4,900	0,000	6710,91	8,398	1,800
Partial draft	5,020	0,000	6913,67	8,225	1,900
Deepest subdivision draft	5,100	0,000	7049,99	8,079	2,000

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation			
	Port side	Starboard side	Required index R
Light service draft	0,83487	0,83268	0,62444
Partial draft	0,82691	0,82674	0,62444
Deepest subdivision draft	0,81565	0,82614	0,62444
Attained index A	**0,82400**	**0,82769**	
Required index R		**0,69383**	
Total attained index		**0,82584**	

E. PDS REPORTS DECREASED GM VALUES

E.1 INITIAL ARRANGEMENT

Probabilistic damage stability report

DELFTSHIP Marine Software

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data	Draft (m)	Trim (m)	Displacement (tonnes)	VCG (m)	GM (m)
Light service draft	4,900	0,000	6710,91	8,598	1,600
Partial draft	5,020	0,000	6913,67	8,425	1,700
Deepest subdivision draft	5,100	0,000	7049,99	8,279	1,800

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation	Port side	Starboard side	Required index R
Light service draft	0,80502	0,80551	0,62444
Partial draft	0,80529	0,80548	0,62444
Deepest subdivision draft	0,80756	0,80755	0,62444
Attained index A	0,80614	0,80632	
Required index R		0,69383	
Total attained index		0,80623	

E.2 RCO I

Probabilistic damage stability report

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data	Draft (m)	Trim (m)	Displacement (tonnes)	VCG (m)	GM (m)
Light service draft	4,900	0,000	6710,91	8,598	1,600
Partial draft	5,020	0,000	6913,67	8,425	1,700
Deepest subdivision draft	5,100	0,000	7049,99	8,279	1,800

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation	Port side	Starboard side	Required index R
Light service draft	0,81117	0,81166	0,62444
Partial draft	0,82082	0,81165	0,62444
Deepest subdivision draft	0,81398	0,81405	0,62444
Attained index A	0,81615	0,81261	
Required index R		0,69383	
Total attained index		0,81438	

E.3 RCO II

Probabilistic damage stability report

DELFTSHIP Marine Software

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data					
	Draft (m)	Trim (m)	Displacement (tonnes)	VCG (m)	GM (m)
Light service draft	4,900	0,000	6710,91	8,598	1,600
Partial draft	5,020	0,000	6913,67	8,425	1,700
Deepest subdivision draft	5,100	0,000	7049,99	8,279	1,800

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation			
	Port side	Starboard side	Required index R
Light service draft	0,81734	0,81767	0,62444
Partial draft	0,81178	0,81200	0,62444
Deepest subdivision draft	0,81077	0,81073	0,62444
Attained index A	0,81249	0,81263	
Required index R		0,69383	
Total attained index		0,81256	

F. PDS REPORTS INCREASED GM VALUES

F.1 INITIAL ARRANGEMENT

Probabilistic damage stability report

DELFTSHIP

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data

	Draft (m)	Trim (m)	Displacement (tonnes)	VCG (m)	GM (m)
Light service draft	4,900	0,000	6710,91	8,198	2,000
Partial draft	5,020	0,000	6913,67	8,025	2,100
Deepest subdivision draft	5,100	0,000	7049,99	7,879	2,200

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation

	Port side	Starboard side	Required index R
Light service draft	0,84665	0,84268	0,62444
Partial draft	0,84178	0,84494	0,62444
Deepest subdivision draft	0,87061	0,87072	0,62444
Attained index A	0,85429	0,85480	
Required index R		0,69383	
Total attained index		0,85454	

F.2 RCO I

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data					
	Draft	Trim	Displacement	VCG	GM
	(m)	(m)	(tonnes)	(m)	(m)
Light service draft	4,900	0,000	6710,91	8,198	2,000
Partial draft	5,020	0,000	6913,67	8,025	2,100
Deepest subdivision draft	5,100	0,000	7049,99	7,879	2,200

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation			
	Port side	Starboard side	Required index R
Light service draft	0,84819	0,84424	0,62444
Partial draft	0,84613	0,84930	0,62444
Deepest subdivision draft	0,87651	0,87662	0,62444
Attained index A	0,85869	0,85921	
Required index R		0,69383	
Total attained index		0,85895	

F.3 RCO II

Probabilistic damage stability report

DELFTSHIP Marine Software

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1

Input data

	Draft	Trim	Displacement	VCG	GM
	(m)	(m)	(tonnes)	(m)	(m)
Light service draft	4,900	0,000	6710,91	8,198	2,000
Partial draft	5,020	0,000	6913,67	8,025	2,100
Deepest subdivision draft	5,100	0,000	7049,99	7,879	2,200

Type of ship	Passenger vessel
Number of persons N1 for whom lifeboats are provided	400
Total number of persons ship is permited to carry in excess of N1	0
N = N1 + 2*N2	400
Wind silhouette	Silhouette 1
Heeling moment due to lauching of survival craft	0,00 (t*m)
Aft terminal	-3,260 (m)
Forward terminal	102,291 (m)
Subdivision length Ls	105,551 (m)
Subdivision beam B	20,200 (m)
Hmax	17,600 (m)

Final results of calculation

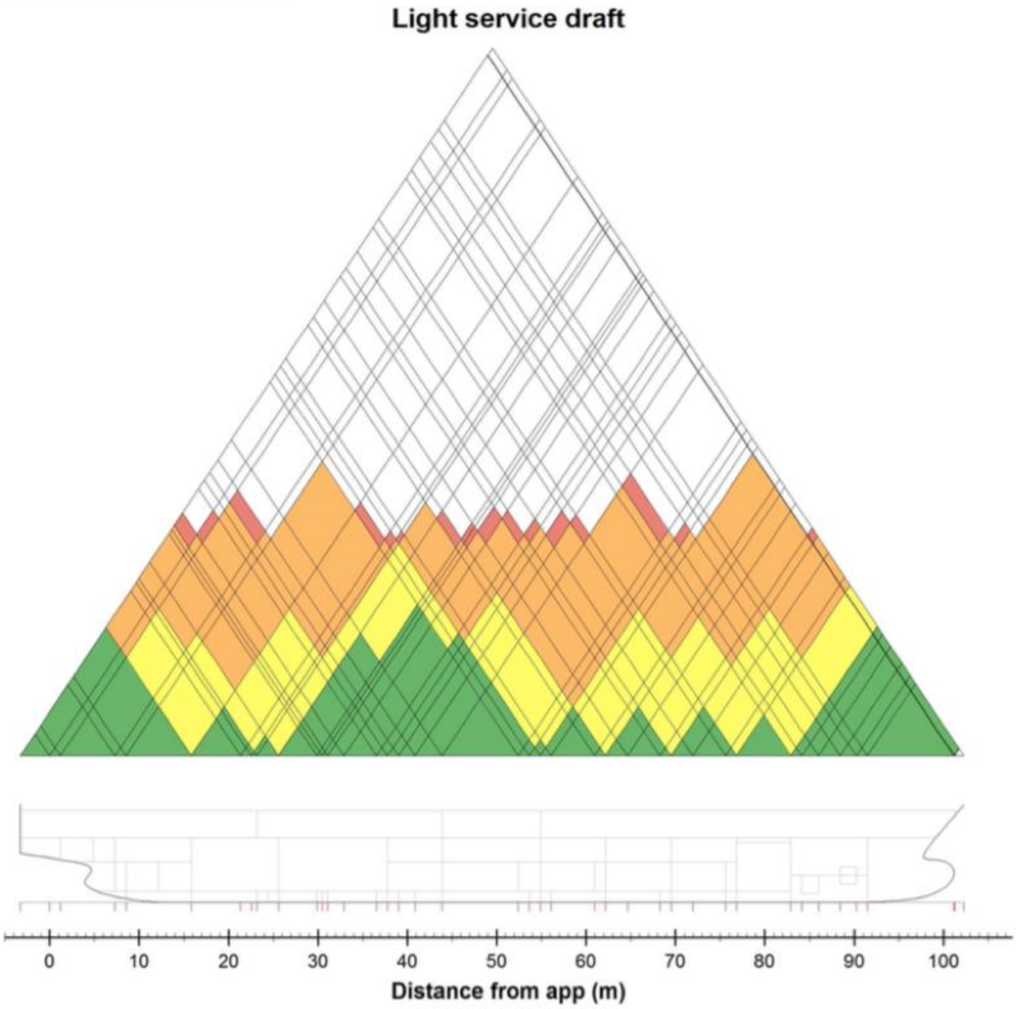
	Port side	Starboard side	Required index R
Light service draft	0,84881	0,84485	0,62444
Partial draft	0,84125	0,84441	0,62444
Deepest subdivision draft	0,86706	0,86709	0,62444
Attained index A	0,85309	0,85357	
Required index R		0,69383	
Total attained index		0,85333	

G. ZONE DAMAGE REPORTS

G.1 INCREASED GM VALUES: INITIAL ARRANGEMENT

Probabilistic damage stability report

Probabilistic damage stability according to Harmonized SOLAS rules 2009 Part B-1



G.2 INCREASED GM VALUES: RCO II