New ships, new rules

Assessment of the Required Subdivision Index for Unmanned Ships based on Equivalent Safety

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By

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Preface

This project has been carried out for the Ship Design Production and Operation department of the Delft University of Technology in order to obtain the Master of Science degree in Marine Technology. Within this thesis I have investigated how the requirement concerning damage stability can be lowered for unmanned ships, while maintaining an equivalent safety level. The development of this work has been supported by others, whom I would like to thank for their contribution.

First of all, I would like to thank Robert Hekkenberg, my daily supervisor. I enjoyed the conversations and discussions we had throughout the project and I have learned continuously from his feedback. I am looking forward to continue to work together in the coming year.

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Contents

Summary

The research effort on autonomous ships has increased over the last years. The realisation of these ships will have as a consequence that the crew can be reduced significantly or even be removed entirely, resulting in unmanned ships. Although there is a strong belief that unmanned ships would lead to more economic efficiency, only limited research has been performed in order to demonstrate what the overall effect of the change to unmanned shipping would have on transport costs. Nonetheless, more reductions in cost or improvement of transport performance for unmanned ships would make them more attractive and economically viable.

The design of a ship is subjected to regulations and requirements that limit the design freedom, but it increases safety. Removing the crew from the ship reduces the risk of shipping, under the assumption that the probability that an incident occurs does not change, since the lives of the crew are no longer at risk. If the risk is lower, the requirements to the design of unmanned ships might become less strict, while maintaining equivalent safety. In this way more design freedom can be realised for unmanned ships, as well as more economic efficiency.

Within this report the required subdivision index will be evaluated, for it is expected that reducing this requirement can create more design freedom. Therefore, this research will focus on:

> "*What reduction in the requirement concerning damage stability for unmanned ships can be allowed, if they are subjected to an equivalent level of risk as manned ships of the same size and type?*"

The method for the evaluation is derived from safety science, in order to achieve equivalent safety. In short, safety means the absence of unacceptable levels of risk. Therefore, the term safety level is related to the term level of risk. In order to find an equivalent safety level, it will suffice to find an equivalent level of risk. Risk is expressed by the probability of an undesired event multiplied by the consequences of that event.

The level of risk of a system is found by means of a risk analysis, which will also be the case in this research. For a ship being damaged by collision or contact, multiple events can happen. These events are defined as damage cases. If it is assumed that the ship will be part of a collision or contact, there is a certain probability that each of the damage cases will happen.

For each damage case it can be calculated what the probability of occurrence is and what the probability of survival is. Subsequently, each damage case has consequences. Multiple damage cases will lead to the consequence of a total ship loss. If the ship is not lost, there will be a combination of loss of cargo, loss of fuel, damaged machinery and steel damage. The risk of losing lives is evaluated separately.

The overall level of risk for a ship that is part of a collision or contact is found by a summation of the risk per damage case and the risk of losing lives. The risk per damage case is found by multiplying the probability of occurrence with the consequences of the damage.

In this research, three manned ships have been evaluated. Ship 1 has a size of 6,000 dwt, ship 2 has a size of 4,000 dwt and ship 3 has a size of 13,000 dwt. In this research, the overall level of risk has been determined for each of these ships. These levels of risk are used as a benchmark for unmanned ships of the same size and type as ship 1, 2 and 3.

It has been found that the required subdivision index can be lowered for unmanned ships, based on equivalent safety. The contribution of the risk of losing lives to the overall level of risk is larger for smaller ships. This is reasonable, since for larger ships, the size of the crew increases with a lower rate compared to the amount of cargo, installed power or capital costs. Therefore, the allowable reduction in the required subdivision index is largest for smaller ships.

However, the size of the reduction depends strongly on missing accident statistics concerning the loss of life. The missing data results in the following uncertainties, for which further research is recommended.

Firstly, for different ship types differences in the accident statistics are present. There are significantly less fatalities related to bulk carriers and container ships compared to general cargo ships. It is expected that these differences are related to the individual ship size and crew size, for which both the correlation with the probability of losing life is unknown.

Secondly, there is a discrepancy between the theoretical probability of survival of a ship, namely the attained subdivision index, and the probability of survival that the accident data suggests. The attained subdivision index suggests that at least 30% of all accidents should lead to a total ship loss. The accident data reveals that for general cargo ships around 10% leads to a total ship loss.

1. Introduction

At the beginning of the 21st century, self-driving cars seemed to be fiction of a faraway future (Davies, 2018). Although people have been dreaming of self-driving cars for decades, up to a few years ago, it was only 'maybe possible' to realise. A lot has changed. Research about self-driving cars has been taken so far, that it is already being tested on public roads. A computer driving you around has gone from being a dream to becoming reality.

The idea of self-driving cars has reached the maritime sector as well. Autonomous ships might not be fiction anymore, although the development is still in its infancy. Over the last years, the research effort on autonomous ships has increased substantially. The realisation of an autonomous ship will have the consequence that the crew can be reduced significantly or even can be removed entirely. The result would be unmanned ships, that can be either remotely controlled or fully autonomous.

Nevertheless, the business case of unmanned ships is still hard to make. As for most innovations within the maritime industry, the incentive for unmanned ships is economic efficiency (Karlis, 2018). Although there is a strong belief that unmanned ships would lead to more economic efficiency, only limited research has been performed in order to demonstrate what the overall effect of the change to unmanned shipping would have on transport costs (Frijters, 2017; Rødseth & Burmeister, 2015). Therefore, this research will focus on the possible increase of economic efficiency of unmanned ships.

1.1. Background

At this moment the crew performs an extensive amount of tasks on a ship. If the crew is to be taken of board, these tasks will have to be eliminated, taken over by machines or performed during port calls. Routine tasks will no longer be performed by the crew while sailing. The next topics show the most important research that is being conducted and the investments that are needed.

Currently routine maintenance in the machinery and elsewhere in the ship is among the tasks of the crew. According to the MUNIN project (Rødseth & Burmeister, 2015), the redundancy in propulsion and energy systems will be a challenge for unmanned ships. If the energy system would fail, the ship could become adrift, forming a danger for surrounding ships and the environment. While on manned ships the crew can intervene by preventive maintenance or immediate repairs, this would not be possible on unmanned ships.

Other important tasks concern navigation and situational awareness. Already, supporting systems are installed on ships, such as autopilot (Saini, 2018). The development of these supporting systems will allow for remote control or even autonomous sailing.

In order to keep control over an unmanned ship, an onshore control centre will be needed with a continuous connection to the ship. The required connection brings other challenges along such as cybersecurity (Bertram, 2017). The ship would need protection against hackers trying to take control over the ship.

These three topics show that the replacement of crew by autonomous or remotely controlled systems requires research and investments. A part of the investments can be covered by the crew wages that will no longer be part of the cost of shipping. However, more reductions in cost or improvements of transport performance for unmanned ships would make them more attractive and feasible.

In order to find a way to reduce the cost or improve the transport performance of unmanned shipping, the requirements for (unmanned) ships will be reviewed. The requirements for ships are, to a great extent, imposed by national laws, the flag-state of the ship, the classification of the ship and, most of all, by the International Maritime Organization (IMO). Reconsidering parts of these regulations for unmanned ships could result in more design freedom, that could result in a reduction in cost or an improvement of transport performance.

Van Hooydonk (Hooydonk, 2014) already states that existing regulations will continue to function with respect to unmanned ships. However, amendments to the existing regulations will have to be made in order to incorporate unmanned shipping, since parts of the requirements for ships concern the presence of crew on board. Some of these requirements would induce irrational limitations for unmanned ships. These requirements focus on the wellbeing of the crew. As an example, the presence of a lifeboat on board would no longer be necessary. Other requirements might need more careful consideration. For instance, DNV GL suggests that the requirement concerning the noise of the propeller could be changed for unmanned ships

(Vartdal, Skjong, & St.Clair, 2018). Currently the noise of the propeller has to be reduced for the comfort of crew, but the noise of the propeller has an influence on marine life as well.

The suggestion that more design freedom can be realised by reviewing the regulations for unmanned ships leads to the research goal that is described in the following paragraph.

1.2. Research goal

When the crew is removed from the ship, the lives of the crew are no longer at risk. This results in a reduction of the risk of shipping, under the assumption that the probability that an incident occurs does not change. If the risk is lower, the requirements to the design of unmanned ships might become less strict, while maintaining an equivalent level of safety. The hypothesis is that in this way more design freedom can be realised for unmanned ships as well as more economic efficiency. The goal of this research will be to test this hypothesis.

To limit the scope of the work, a literature study will be performed in chapter 2. The literature study will show that it is worthwhile to continue with this subject. Also, it will provide guidance on how to proceed with the subject. A method to find one requirement or a set of requirements to evaluate is derived from the literature. The main criteria for the selection of this requirement or set of requirements are that changes in these requirements will affect the ship design and that the changes could lead to more economic efficiency.

In chapter 3 the details of the research and the research questions are presented. The reason for presenting these details later on, is that these details are built on the knowledge of the literature study.

Furthermore, this research will be limited to small seagoing cargo ships. When the ship becomes larger, the size of the crew increases with a lower rate compared to the amount of cargo, installed power or capital costs. Therefore, it is expected that the impact of removing the crew on the risk of shipping is higher for smaller ships. Additionally, unmanned ships, within the context of this research, are defined as ships that do not have any people on board.

1.3. Document structure

In chapter 2 the literature study is presented. The literature study describes how this research is related to work that has already been carried out. In chapter 3 the research questions and the aim of this research are described in more detail. In order to answer the research questions, a method is presented in chapter 4. The procedure described in this chapter will be performed on three ships. The details and results of the risk analysis of the first ship are presented in chapter 5. These results are evaluated in chapter 6, after which it is concluded that two more ships will be analysed. The details and the results of the second and third risk analysis are presented in chapter 7. The results of all three analysis together are evaluated in this chapter as well. Uncertainties in the data results in the conclusion that changes in the regulations can be expected, but that the size of the changes is still unknown. However, in chapter 8 the impact of changes in the regulations on the design of unmanned ships are discussed. Both ends of the range of changes that can be expected are covered. In chapter 9 the conclusions are presented and in chapter 10 recommendations for further research are presented.

2. Literature study

Research towards the performance of unmanned ships is already being conducted. This research mostly addresses systems that will have to be further developed and improved to assure safe shipping when there is no crew on board. Examples are the situational awareness, navigation, decision making and communication (Lockwood et al., 2017). As a consequence, also artificial intelligence and cyber security are mentioned as challenges. Maintenance and redundancy are brought up as areas of interest as well, since maintenance can no longer be conducted during sailing and redundant system will be needed for a reliable ship. Also, liability has been mentioned as a serious topic for discussion, with the main question, who will be to blame when a fault occurs? Far less research has been conducted in the field of regulations and design.

This research will focus on creating design freedom without reducing safety by evaluating the relevant regulations. Within this chapter, the question will be answered whether it is worthwhile to investigate this area. In order to accomplish this, it will be reviewed what has been published on the development of the regulations for unmanned ships first. Second, safety assessments for unmanned ships are discussed to determine how equivalent safety can be ensured when developing regulations for unmanned ships. Third it is discussed what has been published on the design of unmanned ships and what changes in the design can be expected. Last, a summary is presented.

2.1. Regulations

The review of the literature concerning regulations is divided in three parts. First, the view on the future of regulations by the industry is discussed. They call for the need of new regulations for unmanned ships. In response, the IMO is performing a review of the existing regulatory framework. This is discussed in section 2.1.2. After the review of the existing regulatory framework, the development of a new regulatory framework for unmanned ships might be needed. Suggestion that have been made by other parties for the development of a new regulatory framework will be discussed last.

2.1.1. A view on the future

As was mentioned in chapter 1, Van Hooydonk already stated that existing regulations would continue to function with respect to unmanned ships (Hooydonk, 2014). Furthermore, he states that amendments will be necessary, mainly within the safety of unmanned ships. New developed regulations would most probably fall under the International Convention for Safety of Life at Sea (SOLAS).

Van Hooydonk is not the only one addressing the need of amendments within the existing regulations. Next, others that have written about this subject are addressed. Any solutions and suggestions related to the regulations and their impact on the design are discussed.

Lloyds Register (Lockwood et al., 2017) has shared its vision on future autonomous shipping, where we are now and what will need to change and how they believe it will change. Lloyds Register touches multiple of the challenges mentioned in the introduction of this chapter. Although they describe which topics need careful consideration, solutions are not presented.

DNV GL (Vartdal et al., 2018) released a positon paper which addresses similar topics as Lloyds Register. Unlike Lloyds Register, DNV GL describes the changes needed within the regulations more thoroughly. Some examples are given, such as the definition of the word ‘alarm’, which comes up an extensive amount of times when searching for it in the IMO documents. In order to deal with the needed changes, DNV GL gives several solutions of how to proceed.

The IMO regulatory scoping exercise (see section 2.1.2) is considered as one of them, although it is a time consuming task. The solution they present as less time consuming and mostly recommended, is to develop a new code that would fall under SOLAS. Other regulatory instruments would still need amendments, especially when they contain explicit showstoppers.

DNV GL recommends the goal of the new code to be, “Autonomous and remote-controlled ships shall be as safe as conventional ships of the same type”. With this goal they also address the importance of the safety of unmanned ships as was mentioned by Van Hooydonk. This formulation can be directly related to the goal of this research. It says that any changes in the regulations for unmanned ships should not lead to a less safe ship. Therefore, it will be of utmost importance to be able to describe or quantify the safety of manned and unmanned ships. DNV GL also provides tools on how to address this safety requirement. However, the tools mainly cover situational awareness and decision-making and they are not applicable for the evaluation of the overall design.

The vision of Rolls-Royce on the future of autonomous ships is based on a number of questions they believe have the need to be answered (Rolls-Royce, 2016). One of them is, “Are autonomous ships legal (…)?”. With this question they too address the need to examine the existing regulations.

A second question is, “How can an autonomous vessel be made at least as safe as existing ships (…)?”. With this question, Rolls-Royce suggests that the transition to autonomous ships needs careful consideration. For every step of the transition, the safety of the newly implanted idea will have to be evaluated. Remotely controlled unmanned ships are likely to be part of the development towards fully autonomous ships, according to Rolls-Royce.

Finally, Rolls Royce discuss the benefits of the removal of crew. The direct benefits that were found by discussion with the industry are listed as, “more efficient use of fuel, space in ship design and crew and their skills”. How these benefits, such as “more efficient use of space in ship design”, can be achieved, is not discussed. However, this statement shows that there is a believe that the design of unmanned ships can be optimized for more economic efficiency.

There is one study that does not evaluate the regulations directly, but aims to indicate the operational implications that arise for potential shipowners from the existing regulatory framework (Karlis, 2018). Although the goal might be described as different, the conclusion is the same: the existing regulatory framework will need amendments. Furthermore, it is stretched that the issue of liability (who is to blame in case of a fault) is a great contributor to the risk that a shipowner would take when investing in an autonomous ship. A risk that makes investing unattractive. Finally, he states that more research should be conducted about unmanned shipping, since unmanned shipping has the potential to contribute to more economic efficiency.

The statements by Rolls Royce and Karlis show that there is a belief that unmanned shipping can lead to more economic efficiency. It justifies the need of research towards the optimization of the design of unmanned ships to achieve more economic efficiency. Also, the literature that is discussed shows the need of a review of the existing regulatory framework (see also section 2.1.2) and possibly the development of a new regulatory framework (see also section 2.1.3). New developed regulations would probably fall under SOLAS. The requirements for unmanned ships should lead to designs that are at least as safe as conventional ships of the same type, as most explicitly mentioned by DNV GL.

2.1.2. Review of existing regulatory framework

The previously discussed literature showed that a review of the existing regulatory framework will be necessary. A majority of the regulations for ships is established by the IMO. The IMO is currently performing a regulatory scoping exercise (RSE) (IMO, 2018a). The objective has been defined as, “to assess the degree to which the existing regulatory framework under its purview may be affected in order to address Maritime Autonomous Surface Ship (MASS) operations”. This is an important step in the development for unmanned ships, since the result of the RSE will provide insight in “how safe, secure and environmentally sound” MASS operations need to be.

The procedure that is used by the IMO can be used to find the parts of the regulatory framework that might have an impact on the design of unmanned ships. This procedure is discussed briefly. This will also give some insight in the steps that are currently taken in order to make unmanned shipping feasible.

In order to perform the RSE, four degrees of autonomy are defined:

1) “Ship with automated processes and decision support
2) Remotely controlled ship with seafarers on board
3) Remotely controlled ship without seafarers on board
4) Fully autonomous ship”

For the purpose of this research, autonomy levels 3 and 4 are of interest, since these have the consequence that there are no humans on board the ship. The desire of performing operations within these levels of autonomy will have impact on the existing regulatory framework. The current provisions within this framework can be allocated to one of the following categories:

1) "Apply to MASS and preclude MASS operations
2) Apply to MASS and do not preclude MASS operations and require no actions
3) Apply to MASS and do not preclude MASS operations but may need to be amended or clarified, and/or may contain gaps
4) Have no application to MASS operations"

In order to address MASS operations within the regulatory framework, one of the following actions will have to be performed per provision:

1) "Equivalences as provided for by the instruments or developing interpretations
2) Amending existing instruments
3) Developing new instruments
4) None of the above, as a result of the analysis"

A list of instruments related to maritime safety and security is provided. This list of instruments are considered within the RSE to be affected in order to address MASS operations. As was concluded in section 2.1.1, it is expected that after the review of the existing regulations the development of a new regulatory framework will be needed. In the following section the vision of the industry on a new regulatory framework is discussed.

2.1.3. Guidelines for new regulatory framework

A review of the existing regulatory framework will have as a likely consequence that a new regulatory framework for unmanned ships will need to be developed. Three classification societies shared their vision on a new regulatory framework. These three are Bureau Veritas (Bureau Veritas, 2017), DNV GL (DNV GL, 2018) and Lloyds Register (Lloyd's Register, 2017). The latter two also shared their vision on the future of shipping in general as was described in section 2.1.1.

The three guidelines mostly describe how new rules should be developed and on which general principles they should be based. The regulations that are described are mostly qualitative. Bureau Veritas also addresses the importance of safety analyses, however, how they should be used is not discussed. Also, how a required safety level can be determined is not mentioned.

DNV GL is detailed in its guidelines for some parts. The field of visibility is an example for which more detailed guidelines are described. However, the guidelines of DNV GL remain qualitative with respect to the design of unmanned ships. As an example, throughout the document the term "equivalent safety level" is used. According to DNV GL the unmanned ships should have at least an equivalent safety level as the current alternative. This corresponds to the statement of DNV GL that the goal of a new regulatory framework should be "Autonomous and remote-controlled ships shall be as safe as conventional ships of the same type". However, how the safety level can be found and addressed is not mentioned.

Again, the literature in this paragraph shows that there is a need for a revised regulatory framework. Multiple drafts have been generated thereof, although remaining qualitative and mostly addressing the general principles. An urge to develop more specific regulations is expressed. From this it can be concluded that it is worthwhile to further investigate the research goal as described in chapter 1.

The safety of unmanned vessels is addressed by most of the instances as well. Unmanned ships need to be at least as safe as manned ships. The newly developed regulations should ensure this statement. In order to do so, safety assessments will have to be performed. In the next paragraph the use of safety assessments for unmanned shipping is discussed.

2.2. Safety assessment

Within the recommended guidelines for unmanned ships, Bureau Veritas expresses the need for safety analyses. Bureau Veritas is not the only one emphasizing the need of this. The general opinion is that unmanned ships should be at least as safe as conventional ships. If the design of unmanned ships will be reconsidered, the previous statement can only be assured when safety analyses are performed.

At this point, only a few have looked at safety analyses for unmanned ships. Brocken (Brocken, 2016) and Colon (Colon, 2018) both conducted a research towards the unmanned engine room. Within this research they both used safety analyses to evaluate the performance of the unmanned engine room. Their studies show that safety analyses can be used to evaluate the performance of unmanned systems with respect to manned systems.

One article aims to “develop a system-theoretic model for the safety assessment of autonomous merchant vessels" (Wróbel, Montewka, & Kujala, 2018). As the concepts for systems part of autonomous sea going ships are still under development, the authors tried to achieve very general results. With the safety assessment they want to contribute to the evaluation of the performance of systems for autonomous ships. Although the research is not intended for the evaluation of the overall design of an unmanned ship, it shows the importance of safety assessments. With this research they contribute to the desire to be able to design unmanned ships that are as safe as manned ships.

Eleftheria et. al. (Eleftheria, Apostolos, & Markos, 2016) presents an analysis of ship accidents and fatalities. The title of the article, “Statistical analysis of ship accidents and review of safety level”, reveals that the research is aimed at the evaluation of the safety level of ships. However, the safety level is evaluated in qualitative terms by means of number of accidents and rate of fatalities. Therefore, the risks associated with the rate of fatalities cannot directly be compared to other risks associated with the accidents such as the loss of cargo.

This paragraph shows that safety assessments are used within the maritime industry. Also, safety assessments will be needed to evaluate unmanned ships and compare them with manned ships. However, a procedure to compare different categories of risks and to compare the overall safety level of manned and unmanned ships has not been published yet. Such a method will have to be derived in this research from theory from safety science.

2.3. Design

As was concluded in section 2.1.1, an optimization of the design of unmanned ships could lead to more economic efficiency. In this paragraph the published research towards the design of unmanned ships will be reviewed. Although several projects for the development of unmanned ships are on their way, only few statements about the design of these projects are published. The goal of this paragraph is to find what parts of the design could lead to more economic efficiency and what has already been addressed by current research.

The MUNIN project is the only one addressing the new design in more detail (Rødseth & Burmeister, 2015). Although the project looks at the new designs, the focus is on discussing the constraints for developing an unmanned ship. Some of the constraints and changes that are mentioned are noticeable. For instance, that the removal of the crew also means that the accommodation and associated life support systems may be removed. Also, it is suggested to reduce the complexity and number of ship systems that are unlikely to be operated reliably without continuous maintenance. Two ways to realise this are mentioned, namely to change the operated fuel type and to support ballast free operation. For the engine configuration, the most interesting configuration is said to be two electric propulsion motors operating a twin-skeg configuration. This is based on maintenance and fuel savings.

One of the constraints that is mentioned, is that humans will no longer be able to interfere in case of a fire. This means that the fire detection and extinguishing systems must become more extensive. On the other hand, other methods, such as the use of CO_2, may be adopted, since there are no humans on board (stowaways not included).

In the conclusion it is mentioned “that unmanned ships should be designed from scratch for their intended purpose”. In that way the constraints can be handled in a better way and opportunities for more cost-effective designs can be integrated. The opportunities are not discussed in further detail.

Furthermore, MUNIN evaluated the differences in overall costs of a manned bulk carrier and an unmanned bulk carrier (Kretschmann et al., 2015). In this analysis it is expected that the newbuilding price of the unmanned ship will be higher and the unmanned ship would need extra land based services as well. This is compensated by the elimination of crew costs and by better fuel efficiency. In total they expect the average yearly expenses to decrease with 8.6%. However, it is stated that the unmanned ship would be viable under certain circumstances and that the result is associated with a high level of uncertainty.

In their view on the future, DNV GL published limited statements about the design of unmanned ships (Vartdal et al., 2018). Their main statement is that the design will probably change due to new constraints. These new constraints would be in the form of ‘no requirement to accommodate crew’ or ‘less reduction of noise of the propeller required for the comfort of crew’.

DNV GL also has developed a concept for an unmanned shortsea vessel (Tvete, n.d.). The concept is called The ReVolt and is a 100 TEU container ship. A 1:20 model has been built and tested at NTNU. At this point only limited information is published and it is unknown where the project of DNV GL stands at the moment. There are no recent publications about the project found (last publication in 2017).

Kongsberg is involved in two autonomous ship projects. The first one to mention is the Hrönn, being an autonomous offshore support vessel (Kongsberg, 2017b). Within this article, it is announced that the ship will be produced and tested with sea trials in the Trondheim Fjord. No more recent articles are found concerning this project.

The second project is the YARA Birkeland (Kongsberg, 2017c, 2017a). The size of this ship is about the same as the ReVolt, namely 120 TEU. The service speed with 6 knots is significantly lower than that of conventional ships. The influence of this decision on the design of the ship is not published. The ship is driven by two azimuth pods, which are powered by an electric system. A prototype of the design has been tested and the full scale ship will be built in Norway. The ship will start with a crew on board and transit from crew operation to autonomous operation over the testing period. This implies that the design of the ship will have to comply with all the existing regulations for ships and will be of less interest for this research. Latest news is that the ship will be built by VARD and is to be delivered in 2020 (YARA, 2018).

Bertram shares his vision on future shipbuilding and shipping more general (Bertram, 2017). The most interesting subject is the expectation that fuels will shift towards LNG in combination with fuel cells and batteries. This will lead to less emissions and more reliable propulsion. Another interesting conclusion is the expectation that ships will sail with lower speeds, as can be seen with the service speed of the YARA Birkeland. Sailing with lower speeds will change the optimal design of the hull and the propellers. What the impact of these changes will be is not addressed. Whether these topics are opportunities or constraints and what their impact might be is left open.

Within his thesis, Frijters describes which parts of the design are likely to change for unmanned ships (Frijters, 2017). The lightweight, hull form, powering, machinery selection, complement, general arrangement and costing are mentioned as particulars with a high impact on the design. In the research that is conducted in his thesis, the influence on cost by removing crew and crew related equipment, including the bridge, is evaluated. Frijters predicts that a reduction of 15% in building costs and 40% in operational costs can be realised for small ships. Therefore, Frijters shows that unmanned shipping indeed can lead to more economic efficiency. However, the design of the ship has not truly been reconsidered, only those aspects that will become unnecessary have been removed.

This paragraph shows that the research for the design of unmanned ships is emerging, but only just started to develop. Constraints that will arise are being found and presented. Solutions to these constraints are only speculated upon. Any opportunities that could improve the attractiveness of unmanned shipping are not being investigated yet. Thus although there is a belief that improving the design of unmanned ships will lead to more economic efficiency, only limited research has been conducted in this field.

2.4. Summary

The aim of this literature study was to determine whether it is worthwhile to further investigate the research goal mentioned in chapter 1. The research goal was presented as to find more design freedom for unmanned ships by evaluating the current regulations. Paragraph 2.1 showed that a review of the existing regulatory framework is needed and that the development of a new regulatory framework will most likely follow. Also, the paragraph showed that there is a believe that unmanned ships will lead to more economic efficiency. Therefore, it is concluded that it is worthwhile to further investigate the research goal as a first step to develop a part of the regulatory framework for unmanned ships. The newly developed regulations would probably fall under SOLAS.

Second, the literature showed that there is a belief that an optimized design of an unmanned ship can lead to more economic efficiency. This justifies the limitation to investigate those regulations that might have an impact on the design of unmanned ships and are expected to create more design freedom.

The IMO is currently performing a regulatory scoping exercise in order to review the existing regulatory framework. The procedure that is used can be adopted in order to find a part of the regulations that will have an impact on the design of the ship.

The development of any new regulation should be performed with the goal that “Autonomous and remote-controlled ships shall be as safe as conventional ships of the same type” (Vartdal et al., 2018). This statement is published by DNV GL, but other instances published similar statements.

In order to achieve an equivalent safety level, as proposed by DNV-GL, safety assessments will have to be performed. Although safety assessments are being used in different areas within the maritime industry and related to unmanned shipping, these safety assessments cannot be adopted directly. A method to compare the different categories of risk and to compare the overall safety level of manned and unmanned ships will have to be derived from theory from safety science.

Although it has been stated that an optimized design of unmanned ships would lead to more economic efficiency, only limited research has been conducted in this field. Frijters quantified part of the economic efficiency for removing crew and crew related equipment and structures. MUNIN also researched the economic feasibility of unmanned ships. In their analysis it is assumed that the building costs of the ship will increase, but it is concluded that a decrease of the yearly expenses is possible under certain circumstances.

3. Research focus

In the introduction the research goal has been presented as creating design freedom without reducing safety by evaluating the relevant regulations. The literature study showed that it would be worthwhile to further investigate this topic. The study also revealed that new developed requirements for unmanned ships are likely to fall under SOLAS. The development of these new requirements should lead to unmanned ships that are at least as safe as conventional ships of the same type. In this chapter, these conclusions will be used to further develop the details of this research. First, the current regulations in SOLAS will be reviewed and the requirement concerning damage stability will be selected. Thereafter, the requirement concerning damage stability will be discussed. Last, the research question and the sub-questions are presented.

3.1. Evaluation of the existing regulations

First of all, one requirement or a set of requirements will be selected to investigate further. Most of the requirements that concern the safety of crew on board a ship are covered in SOLAS. Since it is expected that the new requirements will fall under SOLAS too, these requirements will be evaluated. The goal of the evaluation is to select one or more requirements for further investigation. These requirements will be selected on two criteria. Firstly, the requirements will need to have an impact on the design of unmanned ships. Secondly, the changes to the design that would be allowed with the new requirements should lead to more economic efficiency.

In chapter 2 it has been mentioned that the IMO is performing a regulatory scoping exercise. The procedure that is used can be adopted for the evaluation of SOLAS. In Table 1 a summary of the evaluation is presented, the full evaluation can be found in appendix A. For each chapter of SOLAS, it is described what amendments can be expected to be needed. Based on these expected amendments, the possible impact on the design is presented. Also, the expected magnitude of the impact on the design is stated.

As can be seen in Table 1, the largest impact can be expected for changes in chapter II. For the first part of chapter II, it is expected that changes to the requirement concerning damage stability might have a large impact on the design. This is partly because the requirement concerning the damage stability is one of the first to limit the design freedom for a naval architect (H. Linskens, personal communication, 9 January 2019)[1]. It can also be expected that the changes to the design will lead to more economic efficiency. This can be achieved by either reducing the number of tanks in the ship, and therefore reducing the building costs, or by increasing the transport capacity, and therefore increasing the earning capacity.

The second part of chapter II covers all regulations related to fire on board. In order to make unmanned shipping possible, these regulations certainly have to change. A part of this chapter demands a response from the crew, while this would not be possible on unmanned ships. The impact on the design can be expected to be large and it may lead to more economic efficiency by reducing the building costs.

Concluding, both parts of chapter II are expected to have a large impact on the design of the ship. In order to make unmanned shipping possible, chapter II-2 must change. Chapter II-1, however, does not need to change necessarily, since the ship can still comply to these regulations without a crew. Although this is an important difference, it is not a criterion for the selection of the requirement. The increase of economic efficiency by changes in the design is expected to be larger for the requirement concerning damage stability, since it might also increase the transport capacity. Therefore, the requirement concerning damage stability (from chapter II-1) will be further investigated in this research.

[1] H. Linskens is a Naval Architect at DEKC Maritime. DEKC Maritime offers concept design, basic design and detailed engineering for new built ships as well as support during the lifetime of a ship. https://www.dekc-maritime.com/about-us/

Table 1: A summary of the evaluation of SOLAS per chapter. In order to incorporate unmanned ships, the regulations within SOLAS might need amendments. The amendments could allow changes in the ship design. The goal of the evaluation is to find the amendments that have the largest impact on the ship design.

Chapter	Changes of regulations	Change of ship design	Impact on design
I: General provisions	Few adaptions needed	None	None
II-1: Construction – Structure, subdivision and stability, machinery and electrical installations	Adaptions to assure unmanned procedures. Adaptions for safe unmanned mechanical and electrical installations. Changes in the stability requirements that ensure safe operations (since the crew is no longer part of the operations).	Damage stability and watertight layout. Intact stability. Doors and openings within structure.	Large
II-2: Construction – Fire protection, fire detection and fire extinction	Needs careful consideration and major adaptions, such that no interactions with and response from the crew is required.	New integrated fire system needed. Structural design might be allowed to change.	Large
III: Life-saving appliances and arrangements	This chapter has in its current state no application on unmanned ships	Remove all equipment and arrangements	Small
IV: Radiocommunications	The chapter needs to be amended such that communication with the ship takes into account that there are no humans on board. The humans involved will be in an on shore control centre.	None	None
V: Safety of navigation	Amendments are needed in order to assure the safety of navigation for a ship that is controlled by a machine or remotely.	Remove bridge, possibly replaced by a mast. Remove pilot transfer arrangements.	Very small
VI: Carriage of cargoes and oil fuels	Few adaptions needed	Possible change in cargo holds	Small
VII: Carriage of dangerous goods	Few adaptions needed	None	None
VIII: Nuclear ships	None	Unknown	Unknown
IX: Management for the safe operation of ships	None	None	None
X: Safety measures for high-speed craft	None	None	None
XI-1: Special measures to enhance maritime safety	None	None	None
XI-2: Special measures to enhance maritime security	Few adaptions needed	None	None
XII: Additional safety measures for bulk carriers	None (Only otherwise if safety analyses indicate that higher risks are acceptable)	Probably none	Probably none
XIII: Verification of compliance	None	None	None
XIV: Safety measures for ships operating in polar waters	None	None	None

3.2. On damage stability

The requirement concerning damage stability is called the required subdivision index (referred to as index R). The attained subdivision index of a ship (referred to as index A) has to be higher than the index R. Regulation 7 from Chapter II-1 part B of SOLAS (IMO, 1980) describes how the index A of a ship is calculated, while regulation 6 from Chapter II-1 part B of SOLAS describes how the index R for a ship is determined. Within this paragraph, the basics of the calculations will be explained.

The index A is a property of the ship. The index A can be considered as a total probability of survival, given that the ship is part of a collision (Papanikolaou & Eliopoulou, 2008). Thus it reflects the ships capability to survive a collision or contact that leads to damage to the hull. The index A is calculated by evaluating the possible damage cases that follow from collision or contact.

A damage case is a situation where one or more adjacent compartments are flooded. How these damage cases are generated is discussed in chapter 4. The probability of occurrence of the damage cases is derived from a study by Lützen on ship collisions (Lützen, 2001). SOLAS prescribes a method to calculate the probability of occurrence for the specific damage case (p_i). The flooding of the compartments has an influence on the stability of the ship. The new stability properties are used to calculate a probability of survival for the specific damage case (s_i).

The ship is considered in three loading conditions. The deepest subdivision draught (d_s) is the waterline which corresponds to the Summer Load Line draught of the ship. The light service draught (d_l) is the service draught corresponding to the lightest anticipated loading and associated tankage, including such ballast as may be necessary for stability and/or immersion. The partial subdivision draught (d_p) is the light service draught plus 60% of the difference between the light service draught and the deepest subdivision draught. For each loading condition a partial index can be calculated (A_s, A_p and A_l) with the properties of the damage cases p_i and s_i that are relevant for that loading condition.

$$A = \sum_i p_i * s_i \qquad (1)$$

The total index A consist of three partial indices corresponding with the three loading conditions as follows:

$$A = 0.4A_s + 0.4A_p + 0.2A_l \qquad (2)$$

Subsequently, the index A has to be higher than the prescribed index R. If the length of the ship (L_S) is over 100 meter, the index R is defined as:

$$R = R_0 = 1 - \frac{128}{L_S + 152} \qquad (3)$$

If the length of the ship is less than 100 meter but greater than 80 meter, the index R is defined as:

$$R = 1 - \frac{1}{1 + \frac{L_S}{100} * \frac{R_0}{1 - R_0}} \qquad (4)$$

If a ship is shorter than 80 meter, there is no requirement concerning its subdivision index.

Concluding the explanation of the calculations, the index A is a property of the ship and it will remain a property of unmanned ships. If the index A of the ship is allowed to be lower, the layout of the ship needs less subdivision in watertight tanks or may be allowed to sail with a lower GM as well (see chapter 8). A reduction of the index R will have as a result that the index A of an unmanned ship is allowed to be reduced. The index R is the actual requirement concerning damage stability and it will be investigated whether this requirement can be lowered for unmanned ships.

3.3. Research questions

In the current index R for cargo ships the size of the crew does not matter (as is apparent from equation (3) and (4)). However, the risk of losing life is part of the consequences of a collision or contact. The hypothesis is that if the ship is unmanned, the consequences will be less and a lower probability of survival could be accepted. As was stated by DNV GL, “Autonomous and remote-controlled ships shall be as safe as conventional ships of the same type” (Vartdal et al., 2018). This principle can be used to determine the magnitude of the allowable reduction in the index R. The reduction in the index R should result in an equivalent safety level. As will be explained in chapter 4, an equivalent safety level corresponds to an equivalent level of risk. Since the level of risk can be determined, the term level of risk will be used in the research questions. This results in the following research question:

> “What reduction in the requirement concerning damage stability for unmanned ships can be allowed, if they are subjected to an equivalent level of risk as manned ships of the same size and type?”

In order to find an answer to the research question, a number of sub-questions need to be addressed. First of all the term ‘equivalent level of risk’ is used in the research question. How this can be quantified and used for the research has to be determined.

1) How can the level of risk of a (unmanned) sea going cargo ship be quantified?

Theory from the field of safety science will be used to find the answer to this question. Answering this question will form a basis on which the method for this study can be based. Also, the answer to this question should make it possible to quantify the level of risk of manned ships.

2) What is the damage stability-related level of risk of a manned ship?

The answer to this question will show what the accepted level of risk is of conventional ships today. The influence of the crew on this level of risk can be determined and the level of risk of manned ships can be compared with the level of risk of unmanned ships.

3) How does the level of risk change if the crew is removed?

The comparison of the level of risk of manned and unmanned ships will reveal the difference between the two. In order to establish an equivalent level of risk, the index R will be altered. This will answer the fourth sub-question, which is formulated as follows:

4) What reduction in the required subdivision index can be allowed for an unmanned ship such that it will have the same level of risk as a similar manned ship?

The answer to this sub-question will almost directly answer the main research question. The result of this sub-question is an allowable reduction in the index R for one or more specific ships. These results can be used to form a more general conclusion and answer the main research question.

Answering these four sub-question make it possible to answer the research question. However, the research question is formed with the believe that a reduction in the requirement concerning damage stability will lead to more economic efficiency. In order to demonstrate whether this believe is just, a fifth sub-question is composed.

5) What is the impact on the design when the ship is subjected to a lower required subdivision index?

The answer of the last question should show what the changes will look like for a ship that is designed with a lower required subdivision index. Also, an indication of the quantification of the changes will be presented.

4. Method

In the previous chapter the research questions have been defined. The method to establish the allowable reduction in the index R is discussed in this chapter. The basis of the method is derived from safety science, which will be elaborated upon first. Next, the theory will be used to determine the level of risk for manned ships. Third, the level of risk for conceptual unmanned ships will be determined. The conceptual unmanned ship is defined by taking the original manned ship without changing anything, except to remove all crew. Fourth, the risk profile of the conceptual unmanned ships need to be revised, such that the level of risk will be equivalent to that of the manned ships. Last, a summary is given.

4.1. Theoretical background

The term equivalent safety level is used in the process of defining the research question of this thesis. This paragraph will focus on describing the definitions of safety and risk, safety level and level of risk and risk analysis. These definitions will provide the basis for a procedure to determine a ships safety level.

4.1.1. Safety and risk

Regularly alternatives or equivalents are proposed for solutions that are normally used. Sometimes these alternatives or equivalents challenge rules, standards and/or regulations. In order to determine if these alternatives or equivalents can be accepted, the IMO published guidelines for their approval in a circular (IMO, 2013). This circular provides insight in the formal procedure that is needed in order to approve an alternative such as unmanned ships. More importantly, this circular provides definitions for some essential concepts.

The first concept to look at is safety. The given definition is: “Safety is the absence of unacceptable levels of risk to life, limb and health (from non-wilful acts)”. Although the IMO restricts safety to the human aspect in this document (life, limb and health), it can be deduced from *Risk: An Introduction* (Ale, 2009) that safety is also applicable to systems where a direct interaction with humans is absent. Therefore, the definition that will be used within this research will be that “safety is the absence of unacceptable levels of risk”.

The second concept to look at is risk, since the definition of safety shows that there is a relation between the two. The IMO provides a definition: “Risk is a measure of the likelihood that an undesirable event will occur together with a measure of the resulting consequence within a specified time”. In other words, risk consists of two independent parts, a probability and a consequence.

The probability is generally expressed as a probability per unit of time, for example per shipyear. The probability can be interpreted as “how often will the event happen (per unit of time)” or “how likely is it that the event will happen (per unit of time)”. The given number is usually between 0 and 1, meaning that an event will not happen and that an event will definitely happen respectively.

The consequence part of risk is more difficult to express, since often different consequences are present, which are expressed in different measures. For instance, the loss of human lives cannot directly be compared to the loss of a financial asset as cargo. However, concepts such as the value of preventing a fatality (VPF) are used such that the comparison can be made.

4.1.2. Safety level and level of risk

The definition of safety shows that safety is closely related to risk. In fact, one goes with the other. Although safety is related to the absence of risk, risk does not have to be absent in order for something to be safe (Ale, 2009). The degree in which a ship, for instance, is safe, can be described by a safety level. Additionally, there will be some acceptable safety level. In order to consider a ship as safe, its safety level must be higher than the acceptable safety level. Due to the relation between safety and risk, the safety level can be found by looking at the level of risk a ship is subjected to.

The relation between level of risk and safety level is such that the lower the level of risk for the ship is, the higher the safety level of the ship will be. For every system applies that there is no such thing as zero risk (Ale, 2009). No matter how much effort is put in, there will always be a chance that something will go wrong, however small that chance may be. An acceptable safety level is found by determining what level of risk is acceptable.

When there is a mention of equivalent safety level, this can be interpreted as that the safety level of two or more systems must be the same. Because of the link between safety level and level of risk, this can also be described as that the two systems must be subjected to the same level of risk.

4.1.3. Risk analysis

The level of risk that a ship is subjected to is found by performing a risk analysis. Within a risk analysis potential harmful events are evaluated. For each event it is determined what the probability is that the event will happen. Next, for each event it is determined what the consequence will be if the event happens. The combination of these two dimensions result in the risk of the event.

When performing a risk analysis, it is important to establish the system that will be analysed. The system could be the drive train of a ship or just the engine. But the system could also be bigger, for example the operational profile of the ship.

Risk analyses can be used in different situations. They can be used to determine the level of risk of a new designed system in its current design phase. This level of risk can be compared to standards and based on these results it can be decided whether changes are needed to improve the safety level of the system. Or, risk analyses can be used to compare two systems, which can be ships for example. The risk analysis of both ships and their operational profile would determine the level of risk (and thus the safety level) of both ships. The comparison of the two would than show which of the two is considered to be more safe.

Various methods are available to perform a risk analysis. The IMO presents the most commonly used techniques for performing a risk analysis in their guidelines for formal safety assessment (IMO, 2018b). It will depend on the purpose of the risk analysis which method is suitable.

For instance, the fault tree analysis can be used to find the events that cause both engines of a ship with two engines to fail and to calculate the probability that it will occur. Within the fault tree, the causal relationship between the events and the failure are shown. An example is shown in Figure 1. In this figure the fault tree for the loss of two engines for a dual-engine airplane is shown, but it can be applicable for a ship with two engines as well. For the top event, the loss of two engines, it is determined what the possible causes are. ε_1 is the probability that engine 1 fails and ε_2 is the probability that engine 2 fails. When in a box 'or' is shown, only one of the preceding events have to happen to cause the succeeding event. When in a box '&' is shown, all preceding events have to happen to cause the succeeding event.

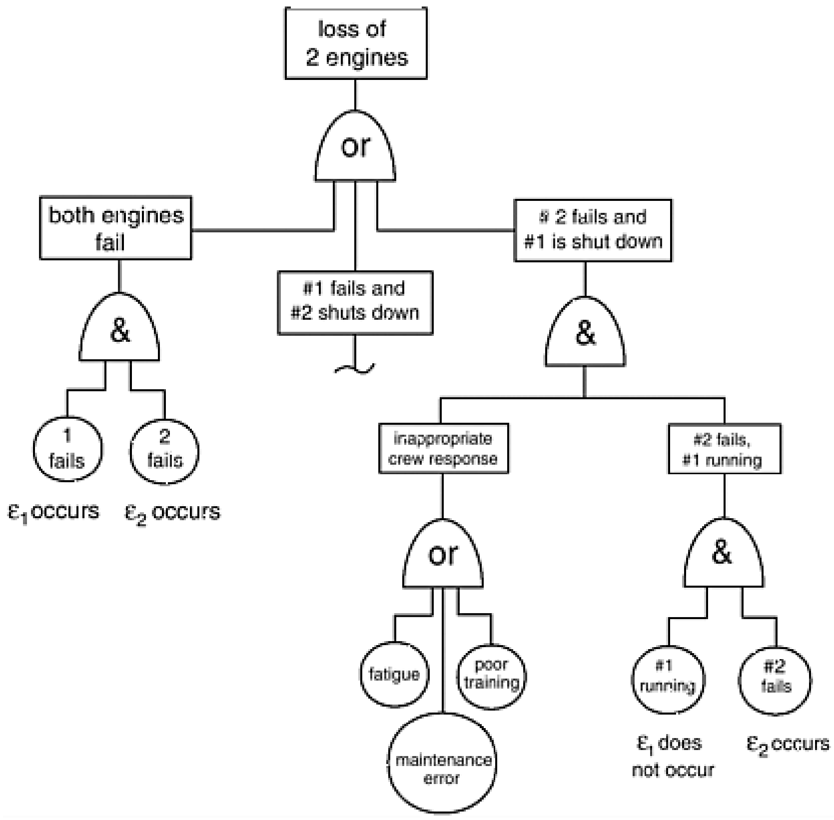

Figure 1: An example of the fault tree for the loss of two engines for a dual-engine airplane. ε_1 is the probability that engine 1 fails and ε_2 is the probability that engine 2 fails. From (National Research Council, 1998).

When the consequences of the failure are of interest, instead of the causal events, the event tree analysis can be used. The event tree analysis is similar to the fault tree analysis, but it shows the effects of the failure and the different paths that can follow from that failure. The event tree analysis can be used to map the most likely paths that can follow and to decide at which point safeguard actions must be applied to mitigate the consequences. In Figure 3 an example is shown, namely a part of the collision risk model for Cruise and RoPax ships that has been used in a study by the European Maritime Safety Agency (EMSA) (European Maritime Safety Agency, 2015b). This risk model is an example of a multi layered event tree with four levels. Per event the probability of occurrence is presented, given that the preceding event has occurred. For each outcome (the last column) the probability is calculated by multiplying each probability on the path that is leading to that outcome. In this example the consequences of the outcomes are given as percentages of human fatalities.

When the risk of an event is found, a stop light chart can be used to determine if the risk is acceptable or not. In Figure 2 an example of a stop light chart is shown. In this chart the two dimensions of risk are plotted against each other. A stop light chart is called that, because of the colours that are normally used; red, orange/yellow and green. If an event falls in the red area (the dark grey area in the top right of Figure 2), the risk of the event is too high. Also indicated in Figure 2 are those events that have such a high consequence that you cannot afford them. These risks will have to be transferred, e.g. by insurance, or entirely mitigated, regardless of the probability. The limit of the level of risk in this graph is presented by a curve. If the level of risk is not below this curve, interference is needed. When an event falls within the orange area (the grey area in the middle of Figure 2), the risk might be allowed, as long as the cost of reducing the level of risk outweigh the benefits of a reduced level of risk. If an event falls in the green area (the light grey area in the lower left of Figure 2) the risk is always acceptable.

The level of risk is susceptible to changes in the two dimensions it consists of, namely the probability that an event occurs and the consequences of that event. If the level of risk of an event appears to be too high, measures can be taken that influence at least one of the two dimensions of risk. For instance, the crew of a ship can be trained, such that they will recognize a hazardous situation earlier and that they know how to act on it. This will influence the probability that the hazardous situation will occur and therefor the risk associated with the hazardous situation. Another example would be the installation of a firefighting system. The system itself will not change the probability that a fire occurs, but it limits the consequences of the fire, and thus the level of risk is reduced.

These measures are used to achieve an acceptable level of risk. If the current level of risk of an event is lower than the acceptable level of risk, some of these measures can be eliminated to cut cost. This will also be the basis of the method of this research. The index R is a measure to limit the consequences of damage due to collision or contact, by limiting the probability of a total ship loss. The level of risk of a manned ship will be taken as the acceptable level of risk for an unmanned ship of the same size and type. The index R for unmanned ships that will result in the same level of risk will be found.

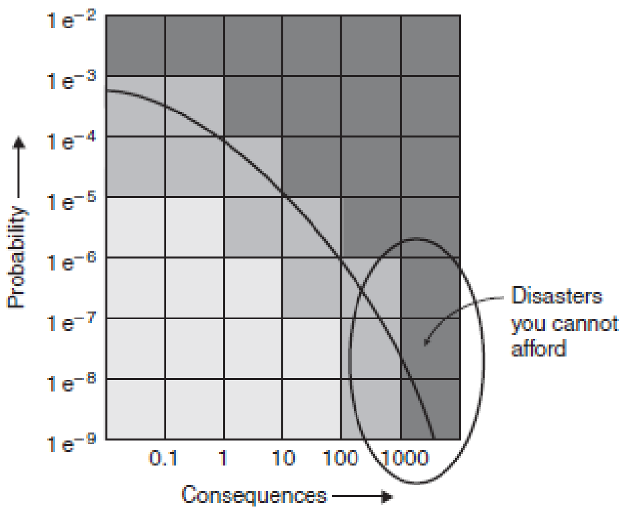

Figure 2: A risk matrix. In this matrix the probability and the consequences are plotted against each other. Any combination of the two is a point in the plot. The colour of the areas indicates the severity of the risk. The dark grey areas have an unacceptable level of risk. In this case, the limit under which all risks have to fall are indicated by a black curve. Also indicated in this plot are those disasters that have such high consequences, that the risks have to be transferred, e.g. by insurance, or entirely mitigated, regardless of the probability. From (Ale, 2009).

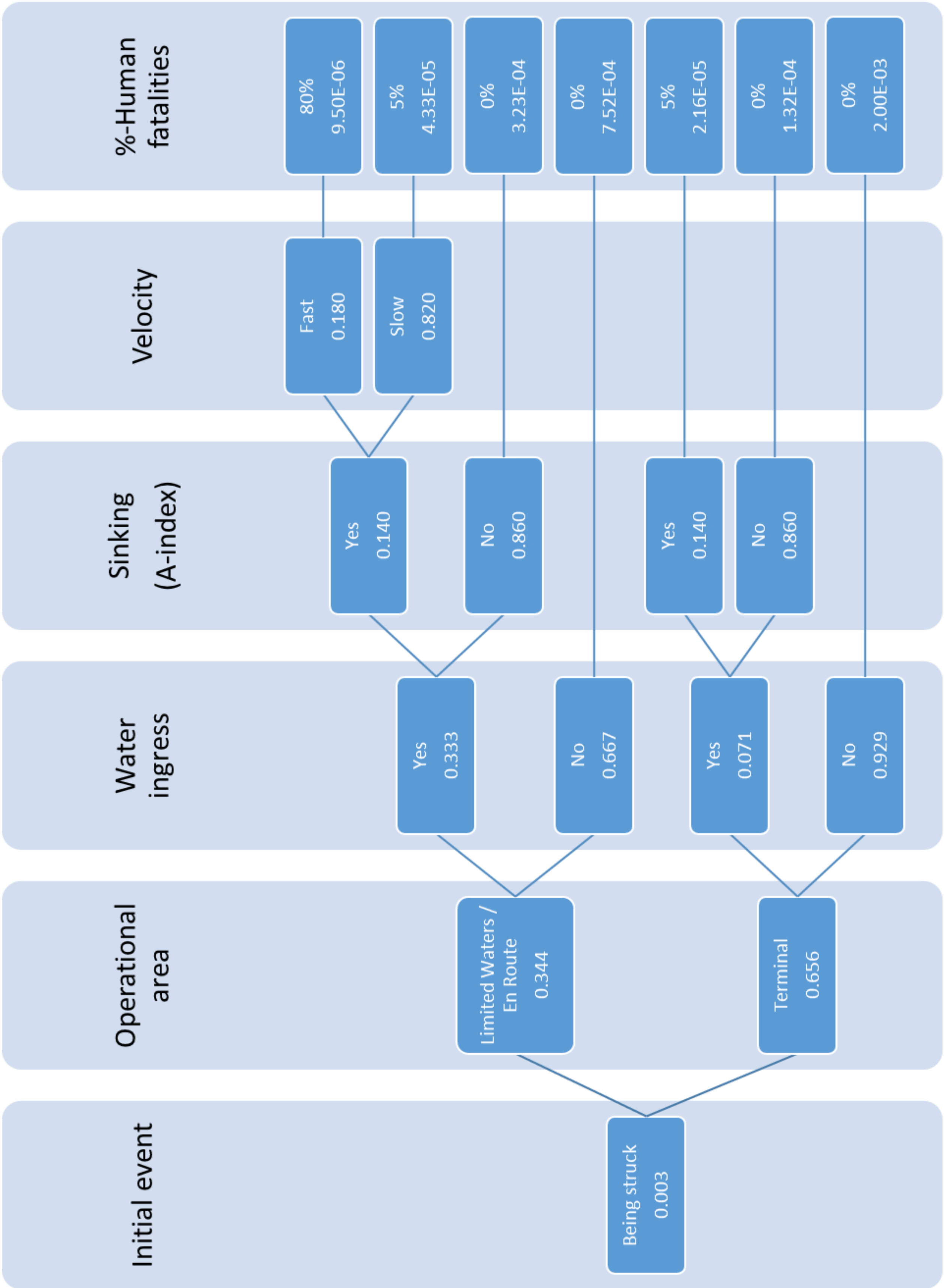

Figure 3: Part of the collision risk model for Cruise and RoPax ship used in a study by EMSA. This model is an example of a multi layered event tree. Per event the probability of occurrence is presented, given that the preceding event has occurred. For each outcome (the last column) the probability is calculated by multiplying each probability on the path that is leading to that outcome. In this example the consequences of the outcomes are given as percentage of human fatalities. Retrieved from (European Maritime Safety Agency, 2015b).

4.1.4. Summary

Concluding this paragraph, it is now clear that safety is the result of an absence of unacceptable level of risk. Where risk can be defined as a combination of the probability on a harmful event and its consequences. Although risk will never be absent, a system can still be considered safe if the level of risk is reasonably low.

The safety level of two or more systems can be compared. Equivalent safety level can be interpreted as the assumption that two or more systems have the same safety level and thus level of risk. Instead of equivalent safety level, it is more convenient to talk about equivalent level of risk. Risks can be calculated and compared with one another.

Risk analyses are used to determine the level of risk. Changes in the level of risk can be made by changing the probability of an event occurring or the severity of the consequences of the event. This will form the basis of the method of this research.

4.2. Developing a risk profile

The previous paragraph showed that in order to achieve an equivalent safety level, an equivalent level of risk should be achieved. In order to achieve an equivalent level of risk, the level of risk of manned ships with respect to damage stability will have to be determined first. A risk analysis will help to determine this level of risk. The general approach of this risk analysis is discussed first. In order to perform the risk analysis, damage cases and the consequences of the damage cases are needed. These two subjects are discussed subsequently. Last, the damage cases and the consequences are linked to generate the overall level of risk.

4.2.1. General approach

In section 4.1.3, it has been mentioned that the IMO presents the most commonly used techniques for performing a risk analysis in their guidelines for formal safety assessment (IMO, 2018b). Of these listed techniques, the event tree analysis is suitable for the risk analysis in this research. As has been described, an event tree is a logic diagram that shows all possible outcomes of an event. The diagram starts with the initial event after which two or more paths lead to different second level events. Depending on the analysis multiple levels can be present.

The event tree that will be used for the risk analysis in this research will consist of one level, as can be seen in a schematic overview in Figure 4. The starting event is the presence of damage to a ship due to collision or contact. It will depend on the cause what the exact kind of damage on the ship will be. A list of possible damage cases are the following events. Each damage case will be of some size in length and penetration depth which results in flooding one or more compartments of the ship. Regulation 7 from Chapter II-I part B of SOLAS (IMO, 1980) describes how the probability of occurrence of any damage case should be calculated. These probabilities take into account that there are different possible causes for the damage. Therefore, any more detail on the initial event will not be needed, since it is incorporated in the details of the following events.

All damage cases have consequences that can be mapped. These consequences do not necessarily all have to be different, e.g. multiple damage cases could lead to the total loss of ship, cargo and crew. In the schematic overview of the event tree in Figure 4, this is shown as well. The first damage case is the event where the aft cargo hold is penetrated. The consequences of the damage case are steel damage and the loss of the amount of cargo in the aft cargo hold, which corresponds to x% of all the cargo the ship is carrying. Damage cases 2 and 4 cause the ship to sink and the consequences are those associated with a total ship loss.

The level of risk is determined by the following procedure. First, for each branch of the event tree, the consequence is multiplied by the probability of occurrence. Then all branches are summed together. This procedure results in one number, which will be used in further steps. Thus the general procedure can be summarized as follows:

$$Risk_k = p_k * C_k \tag{5}$$

$$Risk = \sum_k Risk_k \tag{6}$$

Where:

- k is the set of damage cases
- $Risk_k$ is the associated risk for a particular damage case
- $Risk$ is the overall risk of the ship concerning the effects of collision
- p_k is the probability on a particular damage case
- C_k is the total value of the consequences of a particular damage case expressed in euros.

In order to be able to perform this risk analysis, three more steps have to be taken. First a method to determine the list of damage cases is needed. Thereafter the consequences have to be quantified. Last, the consequences have to be linked to the damage cases in order to find the overall level of risk. These three steps are discussed next.

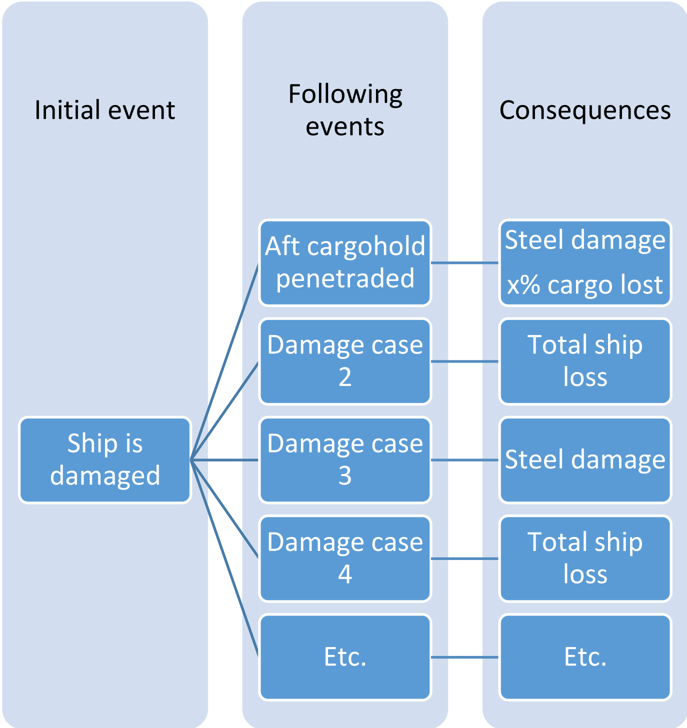

Figure 4: A schematic overview of the event tree concerning damage on a ship. Each damage case is indistinct from one another. The consequences however could be the same, e.g. multiple damage cases could have as a consequence the total loss of ship, cargo and crew.

4.2.2. Defining damage cases

A method to define a list of damage cases is needed. This method will be the same as the current method to evaluate a ships damage stability. The most practical strategy that is used is by defining damage zones over the length of the ship. The boundaries of these zones are chosen to match the watertight boundaries of the layout of the ship. The damage cases are then created by penetrating the hull of one or more adjacent damage zones. The penetration depth is also varied, depending on the number of watertight boundaries over the width of the ship.

Damage zones have to be defined such that defining damage cases is simplified. As mentioned before, a damage case is the flooding of one or more compartments. Therefore, it will be convenient if the penetration of any damage zone will lead to the flooding of maximum one compartment.

In Figure 5 a simplified layout of a cargo ship is shown. Each dotted line corresponds to a watertight boundary. The definition of the damage zones is such that the area between the red lines is damage zone 07. As mentioned above, it will be inconvenient to define damage zone 07 to be larger. If so, the penetration of damage zone 07 would lead to the flooding of two compartments. The flooding of only one of the two compartments is then not evaluated, while it is desired to do so.

Also, it would be inconvenient if damage zone 07 was to be chosen smaller, for instance if it was divided in two, Z07a and Z07b. The penetration of either Z07a or Z07b would lead to the same result, the flooding of the area between the two red lines. Therefore, these two can better be combined into Z07.

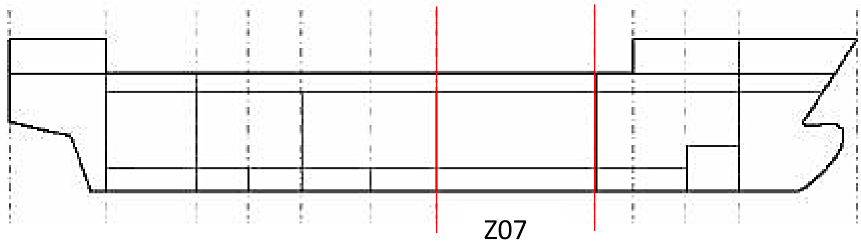

Figure 5: Side view of a simplified layout of a cargo ship. All compartments that are drawn are watertight. The dotted lines correspond with a boundary of a watertight compartment in longitudinal direction. The definition of the damage zones is such that the area between the red lines is damage zone 07. Cross-section image retrieved from (IMO, 2007).

Thus the first step of defining the list of damage cases is to split up the length of ship into damage zones. A damage case consists of the penetration of one or more adjacent damage zones. As mentioned before, the penetration depth is also used to define the list of damage cases, as will be explained next.

As an example, for the ship in Figure 5 a damage case could be the penetration of Z07. Most ships have a double hull and thus will the penetration depth be of importance for which compartments will be flooded. If the penetration depth is less than the width of the double hull, only the compartment next to the shell will be flooded. If the penetration depth is more than the width of the double hull, the cargo hold will also be flooded. Therefore, the damage case is split up in two, Z07.1 and Z07.2. Z07.1 has a penetration depth that is less than the width of the double hull. Z07.2 has a penetration depth that is more than the width of the double hull.

In a similar manner the penetration depth is used for the definition of damage cases over the entire ship. In the final stage of the design of a ship, the layout may consist of an extensive number of compartments. Also, there might be differences between starboard and portside. Therefore, the damage cases are generated for both sides. In the end the list of damage cases can become as large as over 1200 damage cases per side and draft.

The strategy that is described above indicates that the definition of damage zones and damage cases is dependent on the layout of the ship. Therefore, a general approach for performing a risk analysis for a category of ships is impracticable. The risk analysis will initially be performed for one ship. This analysis is meant as an exploration. The acquired results will be evaluated and based on the findings it will be determined how many ships and of which type will be analysed next.

DEKC Maritime provides the designs for the risk analyses. The damage zones have been defined for these designs. As mentioned before, regulation 7 from Chapter II-I part B of SOLAS (IMO, 1980) describes how the probability of occurrence of each damage case can be calculated. The results of these calculations are also provided by DEKC Maritime.

4.2.3. Consequences of damage

Each damage case that has been defined has one or more consequence. The consequences discussed here will be limited to those considered to have a significant contribution on the level of risk. In a nutshell, the damage of a ship can lead to two outcomes, either it will float or it will sink. The consequences if it will sink are covered in the section *Total ship loss*. If the ship will float one or more of the following categories can be the consequence.

- **Loss of cargo** is determined by the loss of value of the cargo. If a cargo hold is penetrated, while the ship remains afloat, it is conservatively assumed that the value of all cargo in and above that cargo hold has lost its value.
- **Loss of fuel** occurs when one or more of the fuel tanks is penetrated, while the ship remains afloat. Fuel oil is a polluting liquid and it will have to be cleaned up.
- **Damaged machinery** occurs when the engine room is penetrated, while the ship remains afloat. It is conservatively assumed that if there is water ingress in the engine room, that the machinery will have lost its value.
- **Steel damage** is a consequence for all damage cases where the ship remains afloat. The collision or contact will have caused damage to the steel structure of the ship and this will have to be repaired.
- **Loss of life** can occur at any time. For instance, the impact of the collision can cause a crew member to be knocked overboard.

How the quantification of each of these consequences is determined is discussed next, including the consequences of *Total ship loss*. Because of the form of the available data for *Loss of life*, this category will be discussed first.

Loss of life

Crew that are present on a ship that is part of a collision are subjected to the potential of losing life (PLL). In order to find the PLL during a collision or contact, data on ship accidents from 2000 to 2012 is used (Eleftheria et al., 2016). In general data on this subject is scarce, due to the fact that sinking seldom occur, compared to the fleet at risk. The data by Eleftheria et al. is a collection and overview of the data available on collisions and fatalities. However, in the data by Eleftheria et al. there is no distinction between fatalities when the ship was lost or stayed afloat. Because of the lack of data on this subject it is unknown what the cause of the fatalities during collision or contact at this point was. Therefore, all fatalities during collision or contact will be assumed to be relevant. Also, the risk of losing life will be calculated independent of the outcome of the accident (whether the ship is lost or not), since the influence thereof is unknown.

The PLL during a collision or contact can be calculated by dividing the number of fatalities during such an event by the number of people that are involved in the event. The latter is unknown, since the size of the crew of the ships involved is unknown. Only the number of ships involved in the event are known. For now the number of ships involved and the number of fatalities will be used to calculate the statistical average loss of life (SALL) per accident. This is calculated by dividing the number of fatalities by the number of ships involved.

Both of these numbers are given as occurrence per shipyear, based on the total fleet at risk over the 13 year period. By multiplying the occurrence per shipyear with the total fleet at risk, the total number of occurrences are found. In Table 2 the numbers and results of the calculations are presented. Since this research is focussed on sea going cargo ships, the statistical average loss of life is calculated for general cargo ships, bulk carriers and containerships for comparison.

Table 2: Finding the statistical average loss of life during collision or contact for general cargo ships, bulk carriers and containerships.

		General Cargo	**Bulk carrier**	**Containership**
Fleet at risk (in shipyears)		118,325	67,822	45,099
Collision or contact	Per shipyear	7.471E-03	7.472E-03	9.383E-03
	Total	884	507	423
Fatalities during collision or contact	Per shipyear	1.881E-03	1.920E-04	8.870E-05
	Total	223	13	4
Statistical average loss of life per accident		0.252	0.026	0.009

As can be seen in Table 2 the SALL differs substantially for the three ship types under consideration. A number of reasons could be the cause. Firstly, it is unknown what the average crew size of each ship type is and thus how many lives are at risk.

Secondly, the sizes of the ships are not defined. General Cargo ships are mainly small and medium sized ships (under 25.000 GT), while half of the bulk carriers and containerships are large or very large (over 25.000 GT) (Equasis, 2012). The size of the ship could have an influence on the SALL. For instance, on larger ships the crew is less likely to be close to the location of impact. Also, the probability of survival is bigger for larger ships, which makes the consequences of the impact likely to be less severe. This can be related to the probability of a total ship loss when a ship is part of a collision. These probabilities are 0 for containerships, 2.36E-04 for bulk carriers and 6.51E-04 for General Cargo ships (Eleftheria et al., 2016). As expected is the probability highest for general cargo ships.

The average size of bulk carriers and containerships is much larger than the size of the ships that will be evaluated in this research. Therefore, the accident data of general cargo ships will be used.

As mentioned in the beginning of this section, the cause of fatalities is unknown. Did the fatalities occur only when the ship was lost? Or did the fatalities occur only when the ship stayed afloat? Or are they evenly distributed over the two situations? In Table 2 it is assumed that the fatalities are evenly distributed. In Table 3 the SALL is calculated again for general cargo, but the result for the two extremes is presented as well.

The second column of Table 3 corresponds to the data in Table 2. It is assumed that the fatalities occur evenly over all accidents. The probability that the considered accidents occur is equal to 1.

The third column of Table 3 shows the SALL if it is assumed that the fatalities occur only if the accident leads to a total ship loss. In this case, the SALL is calculated by dividing the fatalities by the number of total ship loss. The probability that a specific ship is lost is equal to $(1 - A)$. This will have to be taken into account when calculating the risk of losing life. As can be seen, this leads to a SALL that is more than ten times larger.

The fourth column of Table 3 shows the SALL if it is assumed that the fatalities occur only if the ship stays afloat. In this case, the SALL is calculated by dividing the fatalities by the number of ships that were part of an accident but did not sink. The probability that a specific ship is not lost is equal to A. This will have to be taken into account when calculating the risk of losing life.

Because the cause of fatalities is unknown, it will be assumed that the fatalities occur evenly over all accidents for the determination of the risk of losing life. The two extreme cases will be evaluated in chapter 6, as well as the differences between the ship types.

Table 3: The SALL for general cargo ships when the data is interpreted in three different ways.

	Fatalities occur evenly	**Fatalities occur when ship is lost**	**Fatalities occur when ship is not lost**
Fatalities	223	223	223
Ship accidents considered	884	82	802
Statistical average loss of life per accident	0.252	2.720	0.278
Probability of occurrence of accidents	1	1 – A	A

This analysis also reveals another conclusion. In Figure 6 the theoretical and actual probability of survival for a general cargo ship are plotted. The theoretical probability of survival of a ship is the index A, which will be close to the index R. Therefore, the theoretical probability of survival is represented by the index R in this figure. The actual probability of survival is derived from accident data of general cargo ships. The influence of the length of the ship cannot be derived from the available data. Figure 6 shows a discrepancy between the theoretical probability of survival and the actual data.

This might be explained by the calculation of the probability of survival of a damage case. Cichowicz and Murphy also state that the calculation of the probability of survival is flawed and unreliable (Cichowicz & Murphy, 2016). The probability of survival for cargo ships is based on the final stage of flooding. Part of the discrepancy might be explained by the assumption that there will be no interference of the crew in any form. In reality this can be different, although their options might be limited. For instance, the ship can be stranded on purpose in order to prevent a total ship loss or pumps could be activated to reduce the intake of water and improve the stability. However, these actions might also be performed remotely.
Another estimation of the probability of survival is not at hand. Therefore, the index A will be assumed to be the best estimate of the probability of survival for cargo ships in this research.

The SALL can be compared with other risks by using the value of preventing a fatality (VPF). The VPF is a value that represents society's willingness to pay for small reductions of the PLL or SALL. According to EMSA, the VPF is approximately €6.25 million (European Maritime Safety Agency, 2015c).

Besides loss of life the crew can sustain serious injury as well. Injuries entail costs too and should be accounted for in the risk analysis. EMSA describes three methods that are in practical use (European Maritime Safety Agency, 2015c). Each of these methods combines the non-fatal injury risks with the risk of losing life. The current maritime approach takes serious injuries into account with a fraction 0.1 in the total number of fatalities (10 serious injuries is equal to 1 fatality). Minor injuries are accounted for with a fraction 0.01. This method requires data on the probability of injuries. This data is not freely available. Therefore, the influence of injuries in this risk analysis can only be speculated upon. This speculation will not be taken into account in the risk analysis.

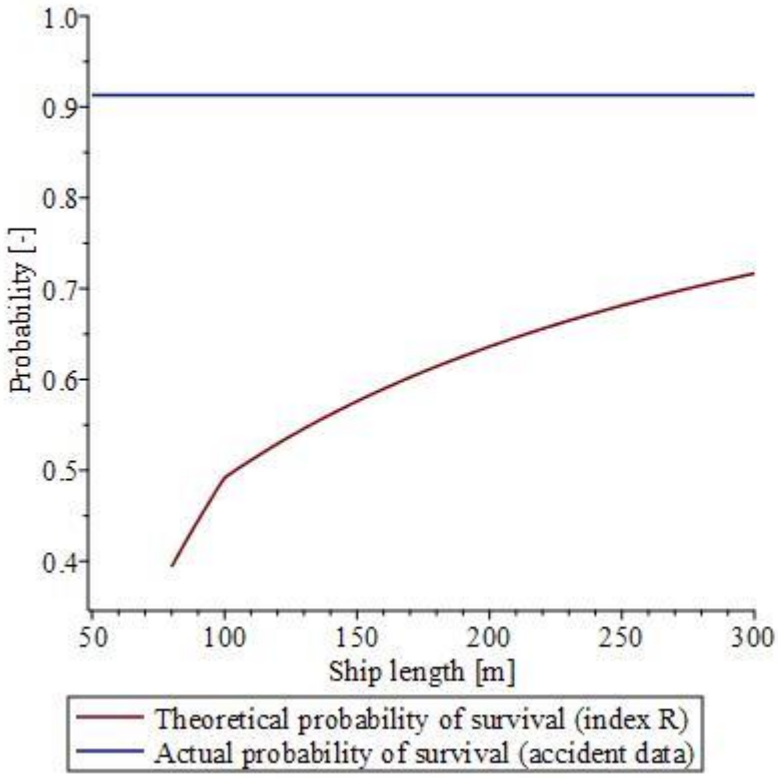

Figure 6: The theoretical and actual probability of survival for a general cargo ship. The theoretical probability of survival of a ship is the index A, which will be close to the index R. Therefore, the theoretical probability of survival is represented by index R in this figure. The actual probability of survival is derived from accident data of general cargo ships. The influence of the length of the ship cannot be derived from the available data.

Concluding, the risk of losing life is dependent on two uncertainties that make it unable to determine this category exactly. Firstly, a difference is noticed between general cargo ships, bulk carriers and containerships. This could be the result of the crew sizes or the length of the ships in these categories. The influence of both parameters on the risk of losing life cannot be determined with the available data. Secondly, the cause of the fatalities is unknown, and therefore it is unknown whether it is more likely to lose lives when the ship is lost or when the ship is not lost.

The SALL for general cargo ships will be used in this research. Also, it is assumed that the fatalities occur evenly over all accidents. The SALL is independent of the size of the ship and the size of the crew and will be taken as 0.252 fatalities per incident. If this number is combined with the VPF, the total risk of losing life is equal to €1,577,000 regardless of the ship under consideration.

Loss of cargo

If a cargo hold is penetrated as a result of a collision, the cargo within the cargo hold will be considered to be lost or at least to have lost its value. To be conservative, the worst case scenario will be evaluated. It will be assumed that any cargo in and above the damaged cargo hold will have lost its value.

The value of the cargo is dependent on the type of cargo. A general cargo ship is designed to be able to transport different types of cargo (Babicz, 2015). Different types of cargos lead to different cargo values. Containers are much more valuable than dry bulk. The most transported dry bulk by ship are coal, iron ore and grain, accounting for nearly two thirds of the dry bulk trade (Chen, 2017). Of these three commodities the most valuable is grain. Its current value is €185 per tonne, which is about three times higher than the value of coal and iron ore (“Wheat vs Coal”, 2019; “Wheat vs Iron Ore”, 2019). The average value (€40,000 (IHS Markit, 2017)) and weight (24 tonnes) of a TEU would lead to a value of around €1,600 per tonne.

For the purpose of this risk analysis, it will be assumed that the ship will transport containers. The maximum amount of containers a ship can transport will be used as the amount of cargo. The value per TEU will be taken as €40,000 (IHS Markit, 2017). In partial loading conditions, 60% of the capacity of each cargo hold is used, in accordance with the definition of the partial loading condition.

Loss of fuel

If a fuel tank is penetrated, the fuel will flow out and that is a threat to the environment. The fuel will need to be cleaned up, which will include costs. These costs can be estimated with the size of the spill (V) in tonnes by $€37{,}819 * V^{0.7233}$ (IMO, 2018b). If the damage case will cause the ship to sink, the clean-up costs are incorporated in the cost of total ship loss.

The value of the fuel that is lost is much lower than the clean-up costs. The price of a tonne of IFO380 on the first of July 2019 is €350 (Ship & Bunker, 2019). If a ship would spill the fuel of a bunker with a size of 100 tonnes, the clean-up costs would be €1.1 million. The value of the fuel would be €35,000, which is only 3.5% of the clean-up costs. Therefore, it is assumed that the value of the fuel can be incorporated in the uncertainty of the actual clean-up costs.

Damaged machinery

The machinery of a ship is expensive and the need to replace this after a collision is a serious consequence. For most cargo ships it can be assumed that most of the expensive equipment is located in the engine room. The penetration and flooding of the engine room is considered to have as a consequence that the equipment in that room will need replacements.

The cost estimation of the engine room will be based on the costs of a new drive train. Aalbers provides a cost estimation for the entire drive train of $€4{,}200 * P^{0.79}$, with P the installed power in kilowatts (Aalbers, n.d.).

Within and near the engine room several tanks are located to store fuel oil, different grades of lube oil and more. As with the loss of fuel, if these liquids are leaked into the environment, clean-up costs will be involved. Although these tanks do not necessarily have to leak any substances when the engine room is penetrated, it is conservatively assumed that they always spill their substances when the engine room is damaged.

Lube oil will be the main polluting liquid in the engine room. Therefore, the clean-up costs of polluting liquids will be based on the amount of lube oil the ship needs with a margin for other spills. The clean-up costs are calculated with the same formula used for loss of fuel, $€37{,}819 * V_e^{0.7233}$, with V_e the total amount of polluting liquids in tonnes in the engine room in tonnes.

Steel damage

Steel damage is considered to occur when the ship is damaged, but not lost. The impact of the accident will cause damage to the hull. Steel damage is, therefore, taken as needed repairs to the steel hull and stiffeners effected by the damage. Also, the ship would need to go in a dry-dock in order to perform the repairs. The cost of these consequences will consist of a constant costs for the ship to be in a dry-dock and a variable costs depending on the size of the damage.

Based on Aalbers (Aalbers, n.d.), the costs of a routine dry-dock for services are within the range of 1% to 2% of the newbuilding price depending on the jobs that have to be carried out. A study by Hansen also shows that the actual costs of being in a dry-dock almost always are underestimated in the quotations carried out beforehand (Hansen, 2013). Taking into account that numerous jobs will have to be carried out besides the repairs of steel damage the higher percentage of Aalbers will be assumed. Also, taking into account some underestimation of the total costs, 50% is added. This results in a total cost to be in a dry-dock equal to 3% of the newbuilding price of the ship.

The variable cost consist of material costs and man-hours. For the material costs €850 per tonne can be used, which includes purchased steel, conservation and an allowance for special materials (Aalbers, n.d.).

The required man-hours can be derived from Butler (Butler, 2013). The man-hours depend on the plate thickness and some correction factors for curvature and location. For an average plate thickness of 12 millimetres 230 man-hours per tonne are required. A factor 1.1 must be applied for high locations that require staging for access. A factor 1.2 for internal structures must be applied. A great part of the repairs will need staging for access and a significant amount of steel will be located internal (e.g. stiffeners). In order to compensate for any corrections not taken into account, both factors will be applied for the entire reparation. This results in an acceptable first estimate of 300 required man-hours per tonne of steel. Taking the man-hour costs as €45 per hour and €850 for the material costs (Aalbers, n.d.) this comes down to a total of around €14,500 per tonne.

In order to find the cost per meter of damage, the cost per tonne have to be multiplied by the estimated number of tonnes of steel per meter damage. An estimation of steel per meter of ship length is found by dividing the weight of the steel of the ship by the length of the ship. Subsequently, two types of damage can be found in the damage cases. Type 1 assumes that only the outer hull is damaged and type 2 assumes that both the inner and outer hull are damaged. The two types and the rough area they comprise are shown in Figure 7. It can be seen that only part of the structure is damaged and will need to be repaired. The exact amount of steel that is damaged will be different per damage case and a rough estimation is made for the average amount.

When looking at the cross-section in Figure 7, the long sides of the side tanks and the double bottom each roughly correspond to ⅙ of the structure. However, not all steel is used in the structure of these walls. Furthermore, the damage cases assume a height of the damage up to the bulkhead deck, which is only part of the depth of the ship. Therefore, it is roughly assumed that the damage of type 1 corresponds to ⅛ of the cross-section and that the damage of type 2 corresponds to ¼ of the cross-section (or twice the amount of type 1). This results in a final variable cost for repairs (per meter of damage) for any ship to be:

$$Cost_{repairs} = €14{,}500 * \frac{steel\ weight}{ship\ length} * \frac{1}{8} * type \quad (7)$$

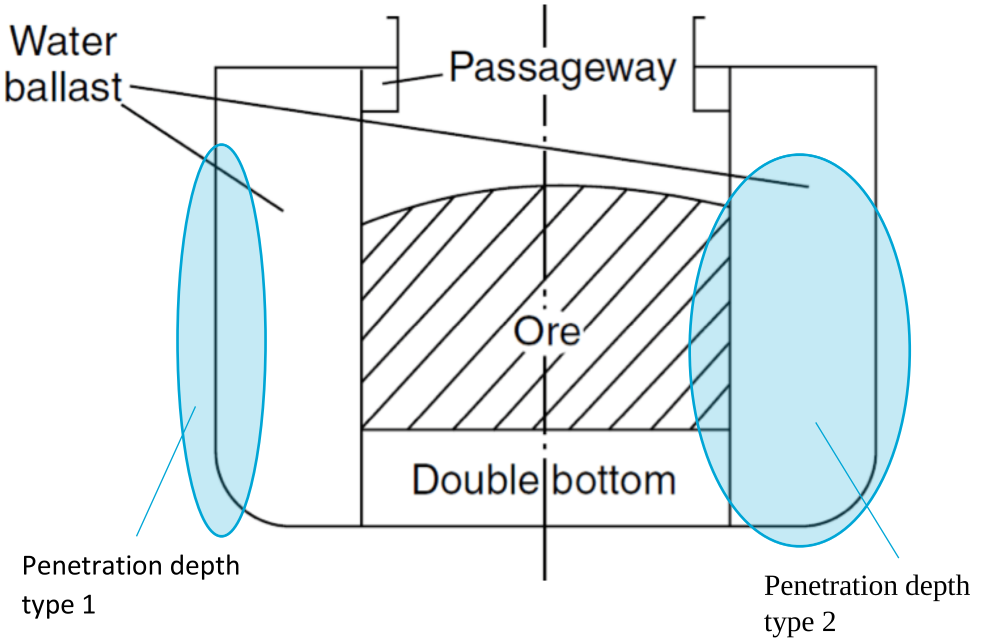

Figure 7: Indication of the two types of damage depending on the penetration depth. Type 1 assumes a penetration of the outer hull only. Type 2 assumes a penetration of both the inner and the outer hull. Cross-section image retrieved from (Chakraborty, 2017).

Total ship loss

In a study by EMSA nine effects of a potential ship loss are mentioned. Not all of these can be quantified and used within the study, as is further explained by EMSA (European Maritime Safety Agency, 2015a).

1) *Human life related accident cost*

   The costs related to the potential loss of life are covered in the section *Loss of life*.

2) *Loss of ship and cargo*

   The value of cargo on board of the ship will be lost. This is equivalent to the calculations for the section *Loss of cargo*. The value of the cargo is taken as the maximum number of TEU a ship can carry, multiplied with the average value of a TEU of €40,000 (IHS Markit, 2017).

   Also, evidently, the ship is lost and the ship has a certain value as well. It is assumed that ships are depreciated over their entire lifetime towards the remaining scrap value of the ship. The scrap value depends on the yard where the ship will be scrapped. Jain mentions €190 per tonne of lightweight ship as a minimum offer price (Jain, 2017). Since this is a study on the potential of losing the ship, it is assumed that on average ships are lost halfway their expected lifetime. Therefore, the value of the ship is taken as halfway its depreciation.

3) *Wreck removal/cleaning costs*
The wreck will have to be removed and cleaning of the environment will be necessary in order to prevent damage to the environment. The cost related to these activities are highly dependent on the circumstances of the accident. However, an expected value can be derived of one to three times the newbuilding price of the ship. In this research, two times the newbuilding price will be taken as costs for wreck removal.

4) *Loss of reputation*
It is most likely that the reputation of the company will be harmed when accidents occur more often. If the reputation of the company has decreased significantly, the company might even need to rebrand in order to survive. However, the reputation of the company is hard to quantify. Even if a quantification is established, there is no data available on how the reputation will be decreased by an accident as well as the costs of a decrease in reputation. Second, since the consequence of the accident will be less severe and an equivalent level of risk is obtained, it will be assumed that the decrease in reputation will not change for unmanned ships.

5) *Loss of income*
Closely related to the loss of reputation is the loss of income. Clients might choose to postpone their freight or choose another company. Especially since the level of risk of sailing the ship might remain the same, while the risk of losing cargo is likely to increase. As for the loss of reputation, the actual decrease of the future income will be hard to quantify and any attempt would be pure guess. Therefore, a loss of income related to (future) reputation will not be considered in this analysis.

6) *Search and rescue*
When an accident occurs with a manned ship, search and rescue might be needed to save all crew. However, many governments do not charge for at sea search and rescue. Also, it is stated that the annual budget for the coast guard and government is depended on more important factors than the number of missions. Therefore, it will be assumed that no significant decrease in costs can be expected.

7) *Accident investigation*
The frequency of accidents is assumed to remain unchanged. Only the outcome of the accident might change. However, in all cases accident investigation is needed and so the number of investigations will not change. The related costs of accident investigation are assumed to be equal for manned and unmanned ships. Therefore, no effect can be expected on the costs of accident investigation.

8) *Legal cost*
The frequency of sinking is expected to increase if the index A of the ship is reduced, while the number of accidents remains the same. Therefore, not the number of lawsuits but the size of the claims will increase. On the other hand, there will be less legal costs involved since there will be no crew related claims. It is acknowledged that further investigation of these numbers might reveal a change in legal costs for unmanned ships. However, the impact of this change will not be considered for this analysis. Because of the principle of equivalent risk, the increase of the overall risk of the ship by reducing the index A must be proportioned to the elimination of the risk of losing life. Therefore, the average increase of the size of the claims is expected to be proportioned with the eliminated crew related claims.

9) *Insurance cost*
The research is conducted with the principle of equivalent risk. This means that the risk of sailing the ship will remain the same. Therefore, it is assumed that the insurance cost will not be affected.

Overview

For convenience, an overview of the categories of consequences that will be taken into account is presented in Table 4. For each category it is summarized how it will be quantified.

Table 4: An overview of the categories of consequence that will be taken into account. For each category it is summarized how it will be quantified.

Loss of cargo	Based on number of TEU's lost Cargo value: €40,000 per TEU
Loss of fuel	Based on volume of spilled fuel (V) in tonnes Clean-up costs: $€37{,}819 * V^{0.7233}$
Damaged machinery	Based on costs of drive-train and spills of polluting liquids (V_e) in tonnes Value: $€4{,}200 * (installed\ power\ in\ kW)^{0.79} + €37{,}819 * V_e^{0.7233}$
Steel damage	Consists of a constant part (docking) and a variable part (repairs) Docking costs: 3% of newbuilding price Repair costs per meter damage: $€14{,}500 * \frac{steel\ weight}{ship\ length} * \frac{1}{8} * type$
Loss of life	Total risk of losing life: €1,577,000 regardless of the ship
Total ship loss	Cargo value: €40,000 per TEU carried Value of ship: halfway its depreciation Wreck removal: 200% of newbuilding price

4.2.4. Combining damage cases and consequences

In the previous two sections it has been defined how the damage cases are found and how the consequences are quantified. In this section it will be explained how the consequences are assigned to the damage cases. First of all, regulation 7 from Chapter II-I part B of SOLAS (IMO, 1980) describes how a probability of survival can be calculated for each damage case. DEKC Maritime will provide the results of these calculations as well.

For each damage case, it will depend on the probability of survival what the consequences will be. In Figure 8 a flowchart is shown to help determine the consequences per damage case. If the probability of survival is 0, the consequence will be a total loss of the ship expressed in a total cost of C_{loss}. If the probability of survival is 1, then the consequence will be a combination of loss of cargo, loss of fuel, damaged machinery and steel damage expressed in a total cost of C_{float}.

However, it is possible that the probability of survival is between 0 and 1. This means that in the final stage of flooding the ship will remain afloat, but that the stability particulars in this situation make it uncertain if the ship will remain afloat. Therefore, there are two possible consequences for such a damage case. The first is what will happen if the ship does not sink, which will happen with a likelihood equal to the given probability of survival. The second is a total loss of the ship, which will happen with a likelihood equal to the complement of the given probability of survival.

$$C_T = C_{float} * s + C_{loss} * (1 - s) \quad (8)$$

Where:

- C_T is the combined total consequence of the particular damage case
- C_{float} is the value of the consequences of the particular damage case when the ship remains afloat
- C_{loss} is the value of the consequences when the ship will sink
- s is the probability of survival of the particular damage case

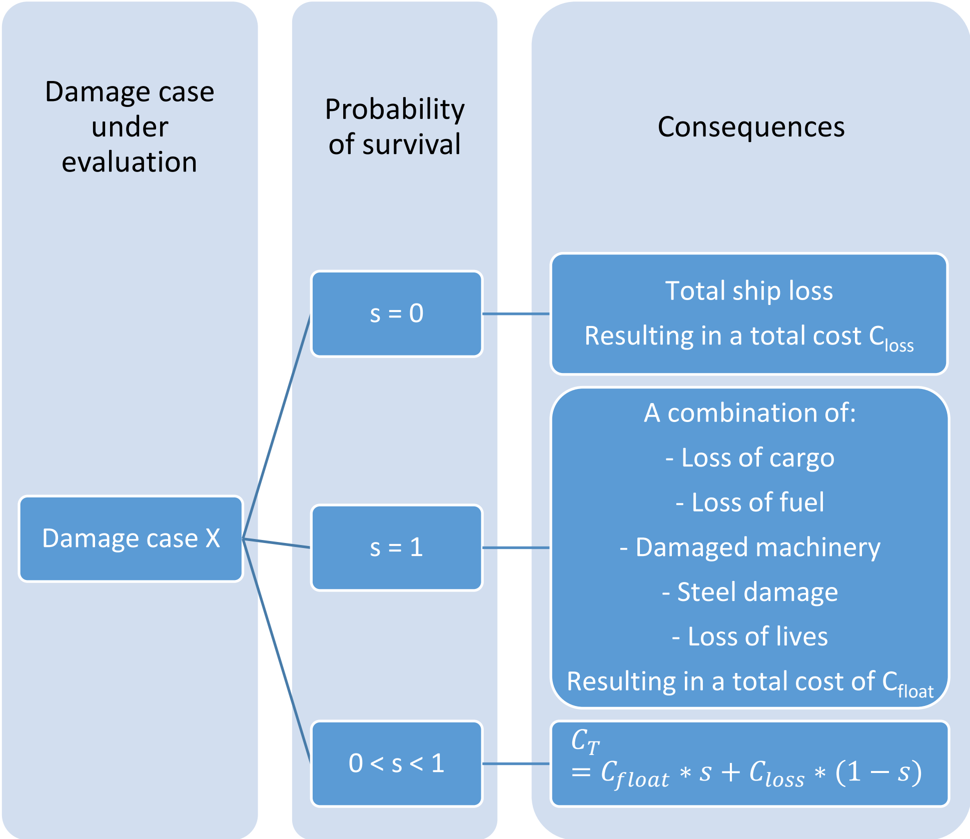

Figure 8: A flow chart to determine the consequences per damage case.

As has been mentioned before, the list of damage cases can become very large. Assigning consequences to each damage case individually can become a time consuming task. Therefore, it will be more convenient to calculate the total risk per category and sum these to create an overall level of risk.

Corresponding to the method to calculate the index A, the ship is considered for three loading conditions: lightweight (d_l), partial loaded (d_p) and fully loaded (summer draft, d_s). For each draft the risk is calculated as an average of portside and starboard, resulting in three risk indices $Risk_s$, $Risk_p$ and $Risk_l$. These are added together as follows:

$$Risk = 0.4 * Risk_s + 0.4 * Risk_p + 0.2 * Risk_l \tag{9}$$

For each category it is shortly discussed how the level of risk is determined.

Loss of life

The risk of losing life has been determined to be €1,577,000 for every ship with a probability of 0.252. This number is not influenced by the damage cases, their probability of occurrence or the resulting probability of survival. In section 4.2.3 it has been described that it is assumed that fatalities occur evenly over all accidents, independent of the outcome of the damage case.

Loss of cargo

Cargo is lost when a cargo hold is damaged, but the ship stays afloat. For each cargo hold a ship has, it can be determined which damage cases would lead to the flooding of the cargo hold. This results in a list of damage cases that lead to the flooding of the cargo hold. For each damage case it is provided what the probability of occurrence (p) and the probability of survival (s) is. This results in a total probability that a cargo hold is damaged and the ship stays afloat per draft. In Table 5 an example of a calculation for a ship with two cargo holds is presented. Per draft and cargo hold the risk is calculated by multiplying the probability with the value of the cargo that is lost. For each cargo hold the total risk is calculated according to equation (9). The combined total risk is a summation of the risk per cargo hold. The combined total risk is also the total risk of losing cargo. The total risk of losing cargo ($Risk_{cargo}$) and the total probability of losing cargo (p_{cargo}) are the two numbers of interest for the following steps (highlighted in green in Table 5).

Table 5: An example of a calculation of the risk of losing cargo for a ship with two cargo holds. The risk per draft is a multiplication of the probability and cargo value. The total risk per cargo hold is the summation of the risk per draft according to equation (9). The combined total risk is the total risk of losing cargo and derived by a summation of the risk per cargo hold. The combined total risk is the total risk of losing cargo.

Draft		**Cargohold Aft**	**Cargohold Front**	**Combined**
d_l	Probability	$p_{l,aft}$	$p_{l,front}$	
	TEU	0% of capacity	0% of capacity	
	Cargo value	€ -	€ -	
	Risk	€ -	€ -	
d_p	Probability	$p_{p,aft}$	$p_{p,front}$	
	TEU	60% of capacity	60% of capacity	
	Cargo value	$Value_{p,aft}$	$Value_{p,aft}$	
	Risk	$Risk_{p,aft}$	$Risk_{p,aft}$	
d_s	Probability	$p_{s,aft}$	$p_{s,front}$	
	TEU	100% of capacity	100% of capacity	
	Cargo value	$Value_{s,aft}$	$Value_{s,front}$	
	Risk	$Risk_{s,aft}$	$Risk_{s,front}$	
Total	Risk	$Risk_{aft}$	$Risk_{front}$	$Risk_{cargo}$
	Probability	p_{aft}	p_{front}	p_{cargo}

Loss of fuel

Fuel is lost when one or more fuel tanks are damaged, while the ship stays afloat. Similar to the calculation described under *Loss of cargo* a total probability that a tank or combination of tanks is damaged is calculated per draft. For the damage of each tank or combination of tanks it can be determined which damage cases will have that as a consequence. The risk per draft and spill is calculated by multiplying the clean-up costs of the spill with the probability. The total risk of losing fuel is the summation of the risk per spill. The total risk of losing fuel ($Risk_{fuel}$) and the total probability of losing fuel (p_{fuel}) are of interest for the following steps.

Damaged machinery

The machinery is damaged when the engine room is flooded, while the ship stays afloat. It can be determined which damage cases lead to the flooding of the engine room. Similar to the calculation described under *Loss of cargo* a total probability that the engine room is flooded is calculated per draft. For each draft the risk is calculated by multiplying the probability with the costs of damaged machinery. The total risk of damaged machinery is a summation of each draft according to equation (9). The total risk of damaged machinery ($Risk_{machinery}$) and the total probability of damaged machinery ($p_{machinery}$) are of interest for the following steps.

Steel damage

For each damage case the length of the damage is known, as well as in which category it falls (see section 4.2.3). Subsequently the costs of steel damage per damage case can be calculated. For each damage case the probability of occurrence and the probability of survival are known. The risk per damage case is calculated by multiplying these two probabilities with the consequences of the damage. The damage cases are provided in Excel, which reduces the time to execute these calculations. For each draft the risk is calculated by summing the risk of all relevant damage cases. The total risk of steel damage is a summation of each draft according to equation (9). The total risk of steel damage ($Risk_{steel}$) and the total probability of steel damage (A) are of interest for the following steps.

Total ship loss

The probability that the ship is lost in each draft is equal to the complement of the partial indices A_s, A_p and A_l. These partial indices give the probability of survival per draft. Therefore, the complements ($1 - A_s$, $1 - A_p$ and $1 - A_l$) give the probability that the ship is lost. For each draft the risk is calculated by multiplying the probability with the consequences of that draft. The total risk of total ship loss is a summation of each draft according to equation (9). The total risk of total ship loss ($Risk_{loss}$) and the total probability that the ship is lost ($1 - A$) are of interest for the following steps.

Overall level of risk

The overall level of risk is found by a summation of the level of risk of the six categories as described above. For each category the total risk and the total probability that it occurs were calculated. This will result in a risk profile of which an example is shown in Table 6.

Table 6: An example of how the risk profile and overall level of risk of a ship will look like.

Category	**Risk**	**Probability**
Loss of cargo	$Risk_{cargo}$	p_{cargo}
Loss of fuel	$Risk_{fuel}$	p_{fuel}
Damaged machinery	$Risk_{machinery}$	$p_{machinery}$
Steel damage	$Risk_{steel}$	A
Loss of life	€1,577,000	0.252
Total ship loss	$Risk_{loss}$	$1 - A$
Overall level of risk	$Risk_{overall}$	
Attained subdivision index		A

4.3. Removing Crew

The goal of the risk analysis is to be able to conclude the influence of the presence of crew on the level of risk of a ship. In order to do so a conceptual unmanned ship is created. As has been described before, this is done by taking the original manned ship and assuming that nothing changes except the presence of the crew. This will result in only one change in the event tree and the risk analysis and that is the possible loss of human lives.

Evaluating the possible influence of the crew on each part of the event tree shows why this statement is true. To start with the initial event: that the ship is damaged is given as a fact. The analysis concerns the possibilities of what can happen after a ship is damaged. The probability that the ship is damaged does not change what happens next.

The damage cases that are considered in the event tree will not change too. These damage cases are based on the layout of the ship and the layout of the ship has not been changed. The probabilities of occurrence for the damage cases are based on a study of ship damages in the past. This implies that the probabilities are determined with the assumption that a captain sails the ship and takes the decisions. If a ship will become unmanned, it will either be remotely controlled or automated. In the first case, the behaviour will most probably not change, since a captain will still make the decisions, but from shore. In the second case, the behaviour of the ship might change and thus the probabilities of where the ship is damaged might change too. However, no data is available on how the behaviour might change and thus on how the probabilities of where the ship is damaged might change. Therefore, it will be assumed that these probabilities will remain the same, since no better alternative is available at this point.

The final part of the event tree is the consequences of the damage cases. In the risk analysis of manned ships the intervention of the crew has not been taken into account. The probability of survival that is calculated is for a passive situation where the stability of the ship is evaluated considering the associated damage case. Also for all other damages, the possible interference of crew has not been accounted for, although their options might be limited. Possible interference of the crew could be activating a pump manually which would result in less severe consequences. However, it is most likely that this is done from the bridge, which means that this can be done remotely from shore. Since the interference of the crew is not taken into account, the consequences of the damage cases will not change if the crew is no longer present.

Concluding, a conceptual unmanned ship is created by removing the crew of any manned ship. Therefore, the risk profile of this unmanned ship is derived from the risk profile of the manned ship. The risk profile will be equal with two changes: the risk of losing life is eliminated, and therefore the overall level of risk will be lower.

4.4. Revised subdivision index

The overall level of risk of the unmanned ship will be changed such that it will become equivalent to the level of risk of the manned ship. Changes in the overall level of risk can be realised by either changing the consequence part of risk or the probability part of risk. Within this research the index A that belongs to the design will be altered in order to change the probability part of risk. The procedure that will be used is a simplified form of the procedure shown in Figure 9. First, the procedure of Figure 9 will be described, after which it will be explained why and how it is simplified.

In Figure 9 the procedure is shown that would lead to a design of an unmanned ship with an equivalent level of risk as a manned ship of the same type. This procedure is an iterative process that is based upon the risk analysis that is described in paragraph 4.2. The initial design of the conceptual unmanned ship is the design of the manned ship it is based upon. The first step in the procedure is to make changes in the layout of the initial design. Changes in the layout of the design that realise a change in the index A could be merging tanks or rooms in the ships subdivision. Reducing the number of tanks and rooms in the ship results in a reduced probability of survival for the damage cases relevant to the changed tanks and rooms. These damage cases will result in a higher amount of water intake. Consequently, this results in a reduced degree of stability after the damage and thus a reduced survivability.

The changes in the layout lead to a new altered design. The damage cases for the new design can be generated and evaluated. The index A that belongs to this new design can be derived from this. Third, the consequences have to be defined. It will depend on the changes in the layout if the consequences will differ from the manned ship. Fourth, the consequences are assigned to damage cases. From this the overall level of risk of the new altered design can be composed. If the overall level of risk is the same as that of the manned ship, the procedure can stop. If the level of risk is not the same, the procedure has to be carried out again until the same level of risk is achieved.

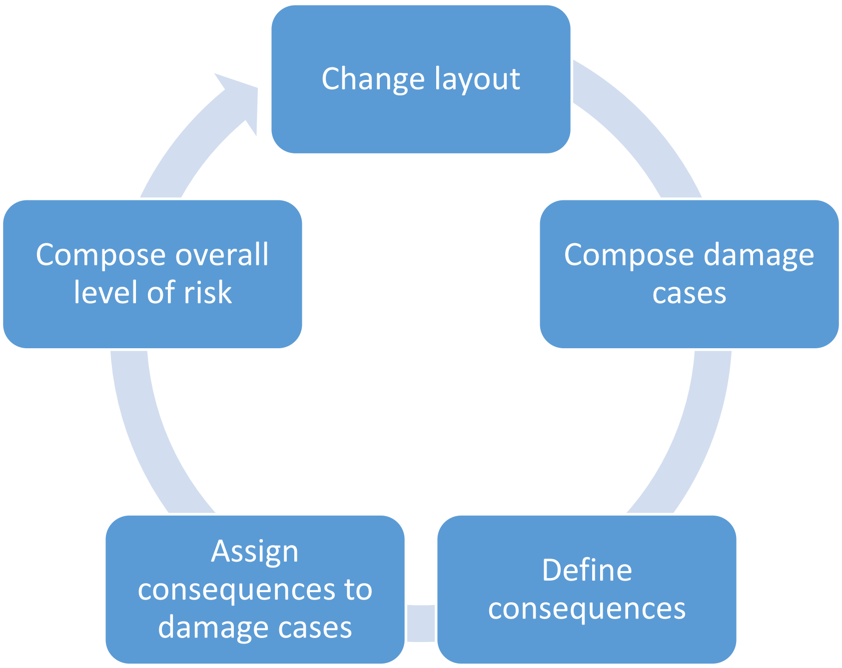

Figure 9: The procedure that would lead to a design of an unmanned ship with an equivalent level of risk as a manned ship of the same type. The iterative process starts with making changes to the layout. Next the list of damage cases has to be composed. The consequences have to be defined. Each damage case will be assigned with the right consequences. Then the overall level of risk can be determined. If this level of risk is not yet correct, appropriate changes to the layout have to be made and the process should be repeated.

The procedure as is shown in Figure 9 is time consuming and making reasonable changes in the layout takes experience in ship design. Also, the procedure will be case sensitive, since the changes in the layout will depend on the layout of the manned ship that is used as an initial design. Moreover, in order to truly rethink the design of unmanned ships for more economic efficiency, the ship should be designed from scratch, without using the manned ship as an initial design. Furthermore, different changes in the layout could lead to the achievement of the correct overall level of risk. Therefore, this procedure is simplified in order to establish a first estimate of the allowable reduction in the index R.

The simplification starts with the assumption that the layout of the design can be altered in such a way that the index A will change. The actual change in the design is not performed. Instead the index A of the unmanned ship is found that would result in an equivalent level of risk.

In Table 6 the categories that would lead to the overall level of risk of a manned ship are shown. For each category the risk has been determined. The risk for each category can be defined as the costs of the consequence multiplied with the probability of occurrence. For each category the probability of occurrence p is determined as well and thus can the costs C per category be determined as well. In the simplification it will be assumed that the costs of the consequences per category will not change for the unmanned ship. In Table 7 an overview is presented of each category that contributes to the overall level of risk for both a manned and an unmanned ship.

Table 7: An overview of the costs of consequence and probabilities of each category that contributes to the overall level of risk for both a manned and an unmanned ship.

	Manned ship			**Unmanned ship**	
Category	**Cost of consequence**	**Probability of occurrence**		**Cost of consequence**	**Probability of occurrence**
Loss of cargo	C_{cargo}	$p_{cargo,m}$		C_{cargo}	$p_{cargo,u}$
Loss of fuel	C_{fuel}	$p_{fuel,m}$		C_{fuel}	$p_{fuel,u}$
Damaged machinery	$C_{machinery}$	$p_{machinery,m}$		$C_{machinery}$	$p_{machinery,u}$
Steel damage	C_{steel}	A_m		C_{steel}	A_u
Loss of life	C_{life}	p_{life}		0	-
Total ship loss	C_{loss}	$1 - A_m$		C_{loss}	$1 - A_u$

From Table 7 it can be derived how the overall level of risk of a manned ship ($Risk_m$) and the overall level of risk of an unmanned ship ($Risk_u$) can be calculated.

$$Risk_m = C_{cargo} * p_{cargo,m} + C_{fuel} * p_{fuel,m} + C_{machinery} * p_{machinery,m} + C_{steel} * A_m + C_{life} * p_{life} + C_{loss} * (1 - A_m) \tag{10}$$

$$Risk_u = C_{cargo} * p_{cargo,u} + C_{fuel} * p_{fuel,u} + C_{machinery} * p_{machinery,u} + C_{steel} * A_u + C_{loss} * (1 - A_u) \tag{11}$$

As was mentioned before, the index A of the unmanned ship (A_u) will be found that assures that the overall level of risk of the unmanned ship will be the same as the overall level of risk of the manned ship. However, the values of $p_{cargo,u}$, $p_{fuel,u}$ and $p_{machinery,u}$ are unknown as well. These values are the total probability that the area of the ship that results in the loss of that category is flooded while the ship survives. If the overall probability of survival of the ship is higher, these probabilities will also be higher. The overall probability of survival of a ship is estimated with the index A. In the simplified procedure it will be assumed that these probabilities will change with the same rate as the index A of the ship will.

$$p_{cargo,u} = p_{cargo,m} * \frac{A_u}{A_m} \tag{12}$$

$$p_{fuel,u} = p_{fuel,m} * \frac{A_u}{A_m} \tag{13}$$

$$p_{machinery,u} = p_{machinery,m} * \frac{A_u}{A_m} \tag{14}$$

These assumptions can be substituted in the formula for $Risk_u$. Thereafter, the equalization of $Risk_u$ and $Risk_m$ has only one unknown term left, namely A_u. This equation can be solved for A_u and, therefore, the index A that will realise an equivalent level of risk is found. The value of A_u can also be found by using a solver to determine the exact value that would solve the equation. The difference between A_u and A_m is the allowable reduction of the index R that ensures an equivalent level of risk.

4.5. Summary

In short, safety means the absence of unacceptable levels of risk. Therefore, the term safety level is related to the level of risk. In order to find an equivalent safety level, it will suffice to find an equivalent level of risk. Risk is expressed by the probability of an undesired event multiplied by the consequences of the event. In general, consequences are expressed in terms of money. Even if this seems unlikely, for instance when human lives are involved, concepts such as the VPF help out to do so anyway.

The level of risk of a system is found by means of a risk analysis, which will also be the case in this research. For a ship being damaged by collision or contact, multiple events can happen. These events are defined as damage cases. If it is assumed that the ship will be part of a collision or contact, there is a certain probability that each of the damage cases will happen. A damage case is defined by a length, depth and location along the hull. For each damage case it is calculated what the probability of occurrence is and what the probability of survival is. These numbers are provided by DEKC Maritime for the ships that will be evaluated in this research.

Each damage case has consequences. Multiple damage cases will lead to the consequence of a total ship loss. If the ship is not lost, there will be a combination of loss of cargo, loss of fuel, damaged machinery and steel damage. The risk of losing lives is evaluated separately. The risk of losing lives is taken as a constant €1,577,000 independent of the ship.

The next step will be to remove the crew from the ship. This will be done by removing the part of the level of risk that is related to the crew. This will result in a level of risk of a conceptual unmanned ship.

The level of risk of the conceptual unmanned ship will be made equal to the level of risk of the manned ship. This will be done by finding the index A for the unmanned ship that will lead to the same level of risk of the manned ship. The procedure that is used to do so is a simplification in order to find a first estimate of the allowable reduction in the index R. Within this procedure, the changes to the design are not performed. The simplification assumes that the design of the ship can be altered such that the index A will change. By changing the index A, the probabilities in the risk analysis will change, and therefore the overall level of risk will change.

The above described procedure will be conducted for one ship first. This analysis is meant as an exploration. An evaluation of the result will indicate which types and sizes of ships should be evaluated next and how many will be needed for a conclusion to be drawn.

5. Risk analysis of a 6,000 dwt ship

In the previous chapter the method that will be used for this research has been described. The method described how the risk profile and the overall level of risk of a manned ship can be determined. Next, it showed how the risk profile and the overall level or risk of an unmanned ship can be determined. Last, it was shown how the allowable reductions in the index R can be found, such that the level of risk of the unmanned ship will be equal to that of the manned ship. In this chapter this procedure is carried out for one ship.

The ship that is selected is discussed first. The quantification of the consequences for this particular ship is presented next. Last, the results of the risk analysis are presented. This will include the following steps of finding an index A for the unmanned version of the ship that will ensure an equivalent level of risk.

5.1. Ship selection

As has been stated before, the expectation is that the effect of removing the crew will be larger for smaller ships. The size of the crew is larger relative to the ship size and amount of cargo for smaller ships compared to bigger ships. For this study DEKC Maritime provided the data of a concept design. Although it is a concept design, it is designed to comply with all regulations and the design is feasible to produce. Also, the design is still in a phase where the layout is simple. The concept design is for a bulk carrier, but with only a few adaptations it could be transformed to a general cargo ship or a containership. For this risk analysis the concept design is taken as a general cargo ship, because of the (lack of) accident data as was discussed in section 4.2.3.

The concept design has a length of 107.4 meters and size of 6,000 DWT. The number of containers it could carry is 300 TEU. On this ship a crew of 8 will be sufficient. The newbuilding price of this ship would be close to €10 million, engineering and building costs included. A ship of this length has an index R of 0.507. However, the provided data shows that this design has an index A of 0.569. This can be explained due to the fact that in the concept phase the ship is designed with a margin towards the index R. These particulars can also be seen in Table 8.

Table 8: Particulars of the concept bulk carrier used in this study.

Ship type	General cargo
Length	107.4 m
Lightweight	1,900 t
Steel weight	1,200 t
DWT	6,000 t
TEU	300
Crew	8
Installed power	2,500 kW
Fuel oil	220 t
Lube oil	15 t
Newbuilding price	€10 million
Required subdivision index	0.507
Attained subdivision index	0.569

The layout of the ship can be seen in Figure 10. The ship has two cargo holds, the light blue areas. In the stern, the grey area, lies the engine room. In the bow, the pink area, is a service space. The ship also has a double hull and double bottom. The tanks around the front cargo hold are U-shaped and thus are portside and starboard connected via the bottom. In the aft, the tanks are separated. The light green areas are the fuel tanks of the ship. All dark green areas are ballast tanks. The white areas are void space. The height of the double bottom is 0.9 meters. The width off the side tanks is 0.8 meters. The bulkhead deck is at 6.6 meters (in the layout this corresponds with the top of the green areas). The spacing distance of the frames is 0.7 meters. The scale in Figure 10 along the length of the ship are the frames.

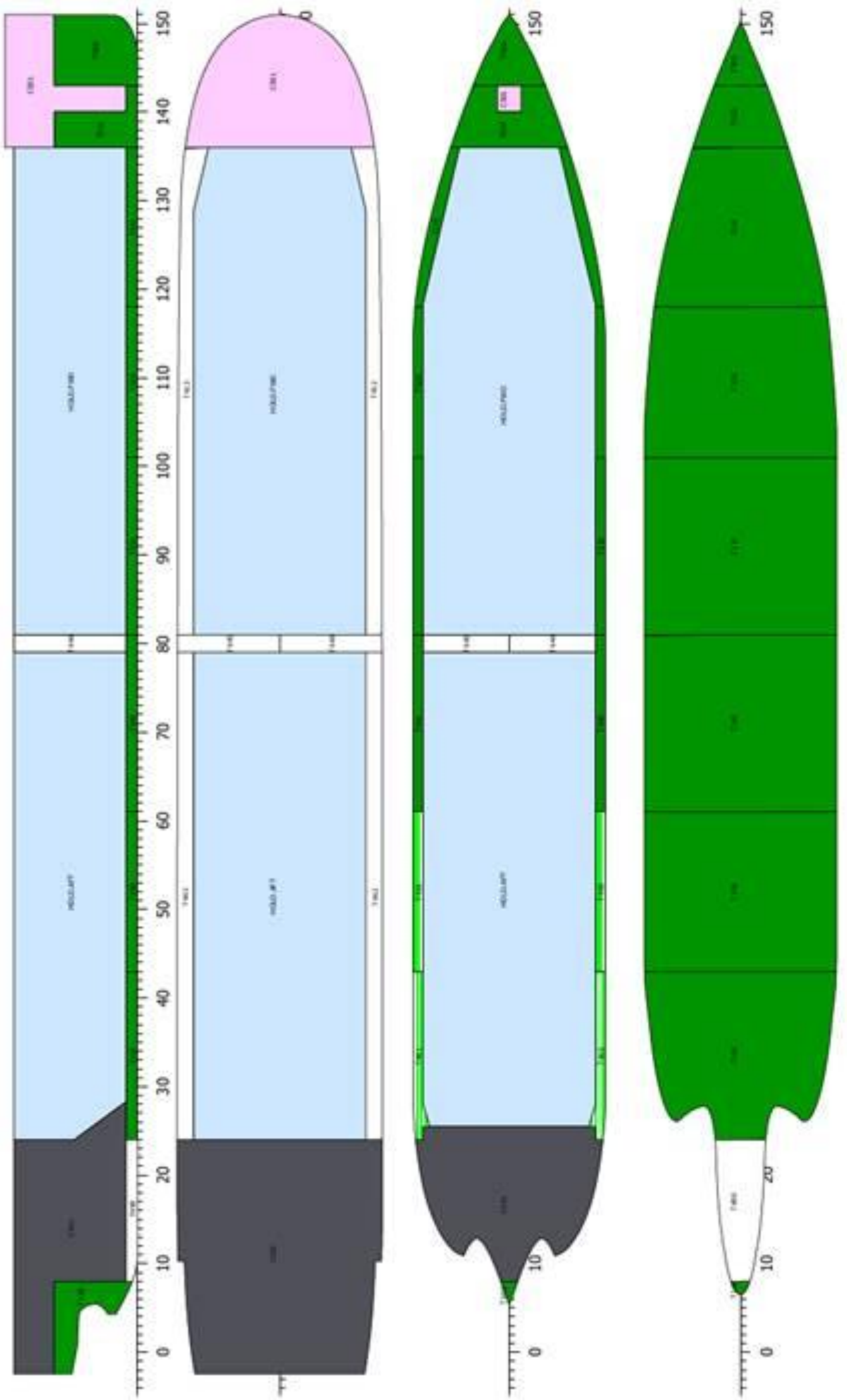

Figure 10: The layout of the concept bulk carrier used in this study. The blue areas are the cargo holds. The grey area is the engine room. The pink area is service space. The white areas are void space. The light green areas are fuel tanks. The dark green areas are ballast tanks. The scale in the length of the ship are the frames with a spacing distance of 0.7 meters.

5.2. Consequences of damage

In order to perform the risk analysis, the values of the consequences need to be known. In this paragraph the consequences related to this ship are described. The quantification of the consequences will be performed according to Table 4 in chapter 4 and by using the values presented in Table 8.

5.2.1. Loss of cargo

The maximum amount of containers this ship can carry is 300 TEU. The ship has two cargo holds of the same size. In the lightest draft the ship will not carry any cargo and the value will be zero. In partial loading condition the value of the cargo in each hold is €3.6 million. In the deepest draft, the value of the cargo in each hold is €6 million.

5.2.2. Loss of fuel

This ship has four fuel tanks of equal size with a combined capacity of 220 tonnes. If one tank will be hit, the clean-up costs are €686,300. If two tanks are hit, the clean-up costs are €1.13 million. Since there are only two tanks on each side, it is assumed that any damage case that damages all four tanks leads to a total ship loss.

5.2.3. Damaged machinery

The cost of the machinery will be estimated with the costs of the entire drive train. These costs are estimated by a value of €2.1 million. The clean-up costs of polluting liquids in the engine room will be incorporated in the costs of a damaged engine room. This ship will need 15 tonnes of lube oil. An extra 5 tonnes is incorporated for any other spills. This results in a total clean-up costs of €330,000 and thus a total costs of damaged machinery of €2.4 million.

5.2.4. Steel damage

The costs estimation of steel damage is considered in two parts. The costs related to dry-docking are taken as 3% of the newbuilding price. This means that the costs related to dry-docking for this ship will be equal to €300,000.

The variable costs are expressed in costs per meter of damage according to $€14{,}500 * \frac{steel\ weight}{ship\ length} * \frac{1}{8} * type$. For this ship this means that the variable costs are equal to $€23{,}000 * type$ per meter.

5.2.5. Loss of life

As has been explained in chapter 4, the risk of losing life will be taken as €1,577,000 regardless of the type and size of ship. This number is calculated by taking the VPF of €6.25 million and multiply it with the SALL of 0.252 lives per accident.

5.2.6. Total ship loss

The cost of a total ship loss consists of three parts: the value of the cargo it is carrying, the cost of the ship and the costs of wreck removal. Since the amount of cargo carried will differ per draft, the cost of a total ship loss will depend on the draft under consideration,. In the lightest draft, the cost of a total ship loss amount €25.2 million. In partial loading condition, the cost of a total ship loss amount €32.4 million. In the deepest draft the cost of a total ship loss amount €37.2 million.

5.3. Calculating risks

In chapter 4 it has been described how the risk per category will be calculated. In this paragraph the calculations per category will be presented.

5.3.1. Loss of cargo

Cargo will be lost when one of the blue areas in Figure 10 is penetrated, while the ship remains afloat. This results in the risk calculation that is presented in Table 9. The total risk of losing cargo for this ship is equal to €654,000 with a probability of 0.109.

Table 9: Calculation of the risk of losing cargo.

Draft		Cargohold aft	Cargohold front	Combined
d_l	Probability	0.282	0.291	
	TEU	0	0	
	Cargo value	€ -	€ -	
	Risk	€ -	€ -	
d_p	Probability	0.187	0.126	
	TEU	90	90	
	Cargo value	€3.6 m	€3.6 m	
	Risk	€672,000	€453,000	
d_s	Probability	0.085	0	
	TEU	150	150	
	Cargo value	€6 m	€6 m	
	Risk	€ 509,000	€ -	
Total	Risk	€473,000	€181,000	€654,000
	Probability	0.079	0.030	0.109

5.3.2. Loss of fuel

Fuel will be lost when the fuel tanks are penetrated, which are the light green areas in Figure 10, while the ship remains afloat. This results in the risk calculation that is presented in Table 10. The total risk of losing fuel for this ship is equal to €120,000 with a probability of 0.155.

Table 10: Calculation of the risk of losing fuel.

Draft		**Fuel tank aft**	**Fuel tank front**	**Both**	**Combined**
d_l	Probability	0.091	0.090	0.048	
	Tank size	55	55	110	
	Costs	€686,000	€686,000	€1.1 m	
	Risk	€63,000	€62,000	€54,000	
d_p	Probability	0.042	0.089	0.041	
	Tank size	55	55	110	
	Costs	€686,000	€686,000	€1.1 m	
	Risk	€29,000	€61,000	€47,000	
d_s	Probability	0.041	0.051	0.010	
	Tank size	55	55	110	
	Costs	€686,000	€686,000	€1.1 m	
	Risk	€28,000	€35,000	€11,000	
Total	Risk	€35,000	€51,000	€34,000	€120,000
	Probability	0.051	0.074	0.030	0.155

5.3.3. Damaged machinery

The machinery will be damaged when the engine room is penetrated, while the ship remains afloat. The engine room is the grey area in Figure 10. This results in the risk calculation that is presented in Table 11. The total risk of damaged machinery for this ship is equal to €369,000 with a probability of 0.156.

Table 11: Calculation of the risk of damaged machinery.

Draft		
d_l	Probability	0.189
	ER value	€2.4 m
	Risk	€447,000
d_p	Probability	0.145
	ER value	€2.4 m
	Risk	€342,000
d_s	Probability	0.151
	ER value	€2.4 m
	Risk	€356,000
Total	Risk	€369,000
	Probability	0.156

5.3.4. Steel damage

Every damage case where the ship remains afloat will have steel damage as a consequence. This results in the risk calculation that is presented in Table 12. The total risk of steel damage for this ship is equal to €466,000 with a probability of 0.574 (equal to the index A of this ship).

Table 12: Calculation of the risk of steel damage.

Draft		
d_l	Probability	0.878
	Risk	€823,000
d_p	Probability	0.625
	Risk	€514,000
d_s	Probability	0.370
	Risk	€239,000
Total	Risk	€466,000
	Probability	0.574

5.3.5. Loss of life

As has been explained in chapter 4, the risk of losing life will be taken as €1,577,000 regardless of the type and size of ship. This number is calculated by taking the VPF of €6.25 million and multiply it with the SALL of 0.252 lives per accident.

5.3.6. Total ship loss

The probability that the ship is lost is exactly the complement of the index A for each draft. This results in the risk calculation that is presented in Table 13. The risk of total ship loss for this ship is equal to €14,758,000 with a probability of 0.426.

Table 13: Calculation of the risk of total ship loss.

Draft		
d_l	A	0.878
	$1 - A$	0.122
	Value	€25.2 m
	Risk	€3,076,000
d_p	A	0.625
	$1 - A$	0.375
	Value	€32.4 m
	Risk	€ 12,133,000
d_s	A	0.370
	$1 - A$	0.630
	Value	€37.2 m
	Risk	€23,415,000
Total	A	0.574
	$1 - A$	0.426
	Risk	€14,835,000

5.4. Results

The overall level of risk of a manned ship is the summation of the risks that have been discussed before. An overview of the risk profile of this ship is given in Table 14. The overall level of risk of this ship is equal to €18,020,000.

Table 14: Overview of the risk profile and overall level of risk of a manned ship.

Type	Risk	Probability
Loss of cargo	€654,000	0.109
Loss of fuel	€120,000	0.155
Damaged machinery	€369,000	0.156
Steel damage	€466,000	0.574
Loss of life	€1,577,000	0.252
Loss of ship	€14,835,000	0.426
Overall level of risk	€18,020,000	
Attained subdivision index		0.574

Removing loss of life from the risk profile results in a level of risk without crew of €16.4 million. This risk will be made equal to the risk of a manned ship of €18 million according to the procedure described in paragraph 4.4. An overview of the risk profile of the new unmanned ship is given in Table 15. The index A of the unmanned ship would need to be equal to 0.525. The reduction in the index A is 0.049 or 8.6% with respect to the index A of the manned ship. Consequently, the allowable reduction in the index R for this ship is 8.6%.

Table 15: Overview of the risk profile and overall level of risk of an unmanned version of the evaluated ship.

Type	Risk	Probability
Loss of cargo	€598,000	0.100
Loss of fuel	€110,000	0.142
Damaged machinery	€337,000	0.143
Steel damage	€426,000	0.525
Loss of life	€ -	-
Loss of ship	€16,549,000	0.475
Overall level of risk	€18,020,000	
Attained subdivision index		0.525

6. Evaluation of a 6,000 dwt ship

In the previous chapter the results of the risk analysis of a 6000 dwt ship are presented. In this chapter these results will be evaluated. First, the sensitivity of the result to changes in the used data is discussed. Thereafter, the further steps that will be taken are presented.

6.1. Sensitivity study

The risk analysis in chapter 5 is based on data that has been established in chapter 4. In this paragraph the sensitivity of the risk analysis for changes in the data is presented. Per risk category the established data is changed to a reasonable alternative and the effect on the result is presented.

6.1.1. Loss of cargo

The concept design that is used for the risk analysis is evaluated as a general cargo ship. A general cargo ship is designed to be able to transport a variety of cargo. If the ship would carry dry bulk, such as grain, the value of the cargo will be different. As was presented in chapter 4, the value of grain is only €185 per tonne ("Wheat vs Iron Ore", 2019). This results in a value of the cargo for a fully loaded ship to be €1.1 million. This is ten times lower compared to the situation where containers are carried with a value of €40,000 per TEU (IHS Markit, 2017). The value of the cargo for a fully loaded ship with containers is €12 million. The comparison of the two cases can be seen in Table 16.

The contribution of the risk of losing cargo, while the ship remains afloat, to the overall level of risk is small, since the probability on this event is small. Therefore, the change in the risk of losing cargo has only little influence on the allowable reduction in the index R. However, the increase of the value of cargo also increases the value of a total ship loss. The probability on this event is significant and it is responsible for the greater part of the overall level of risk. If this value decreases, it can be expected that the influence of removing the crew will be larger, since the value of cargo and ship has shrunk with respect to the crew. This can also be seen in the allowable reduction in the index R, which increases with 32.7%. A decrease in the value of the cargo allows the index R to be reduced further.

Table 16: The influence of the value of the cargo on the allowable reduction in the index R.

	Risk		Attained subdivision index	Allowable reduction
Original	€18,020,000	Manned	0.574	
		Unmanned	0.525	-0.049
Lower cargo value	€13,704,000	Manned	0.574	
		Unmanned	0.509	-0.065

6.1.2. Loss of fuel

The size of the fuel tanks of this ship are small compared to other ships[2]. In order to see the influence of loss of fuel, it will be assumed that the ship is designed to carry twice as much fuel. In Table 17 the results are presented. Carrying twice as much fuel has only little influence on the change in the index A. Although the clean-up costs of the fuel are high, the probability on the event is low. Therefore, the contribution of the risk of losing fuel to the overall level of risk is small. The allowable reduction in the index R increases with only 2%

[2] As reference, see the details of the 4,000 dwt ship in chapter 7. This is a smaller ship, but carries a total of 308 tonnes of fuel.

Table 17: The influence of the amount of fuel on the allowable reduction in the index R.

	Risk		Attained subdivision index	Allowable reduction
Original	€18,020,000	Manned	0.574	
		Unmanned	0.525	-0.049
More fuel carried	€18,080,000	Manned	0.574	
		Unmanned	0.524	-0.050

6.1.3. Damaged machinery

In order to see the influence of the value of the engine room, it will be assumed that there is special equipment present in the engine room. This will increase its value by a factor 1.5 from €2 million to €3 million.

In Table 18 the results of this change can be seen. Although the engine room is expensive, the probability of the event still limits the risk of damaged machinery. The influence of a more expensive engine room is, therefore, only little. The allowable reduction in the index R increases with only 2%.

Table 18: The influence of the value of the engine room on the allowable reduction in the index R.

	Risk		Attained subdivision index	Allowable reduction
Original	€18,020,000	Manned	0.574	
		Unmanned	0.525	-0.049
More expensive engine room	€18,178,000	Manned	0.574	
		Unmanned	0.524	-0.050

6.1.4. Steel damage

The influence of the costs of steel damage will be split in two. First, the costs of dry-docking are evaluated. In order to do so it is assumed that the costs of dry-docking for ship repairs have been underestimated by a factor 2 and that these costs would need to be €600,000 instead of €300,000.

Second, the costs of the reparation of the steel damage is evaluated. Therefore, it is assumed that these costs also have been underestimated by a factor 2. The costs per meter of damage should thus be €46,000 per meter if only the outer hull is damaged and € 92,000 per meter if both the inner and outer hull are damaged.

In Table 19 the results can be seen. Although the changes in costs are large, the influence on the allowable reduction in the index R is only little. The risk of losing the ship outweighs the risk of steel damage by a factor 20. In order to have any more influence, the costs of steel damage have to be much higher. The evaluated changes in docking costs and repair costs both increase the allowable reduction in the index R with only 2%.

Table 19: The influence of the costs of repairs on the allowable reduction in the index R.

	Risk		Attained subdivision index	Allowable reduction
Original	€18,020,000	Manned	0.574	
		Unmanned	0.525	-0.049
Higher dry-docking costs	€18,192,000	Manned	0.574	
		Unmanned	0.524	-0.050
Higher repair costs	€18,314,000	Manned	0.574	
		Unmanned	0.524	-0.050

6.1.5. Loss of life

As was concluded in chapter 4, the risk of losing life depends on four uncertainties. The influence of two of these uncertainties are evaluated. First of all, there seems to be a difference between general cargo ships, bulk carriers and containerships. The SALL for these three ship types are 0.252, 0.026 and 0.009 respectively. The risk of losing life is, therefore, different for each ship type. The risk of losing life of bulk carriers and containerships is about 10 and 20 times lower respectively. The allowable reduction in the index R for these three ship types are shown in Table 20. The allowable reduction in the index R is much lower for bulk carriers and containerships.

Table 20: The index A that results in an equivalent level of risk and the allowable reduction in the index R for different ship types. The results associated with general cargo ships correspond to the results of chapter 4.

	General Cargo	Bulk Carrier	Container ship
SALL	0.252	0.026	0.009
Risk of losing life	€ 1,577,000	€ 160,000	€ 59,000
A_{new}	0.525	0.569	0.572
Allowable reduction	-0.049	-0.005	-0.002
%	-8.6%	-0.9%	-0.3%

The second uncertainty that will be evaluated is the cause of the fatalities. As has been explained in chapter 4, it is unknown how many fatalities occurred during accidents that lead to a total ship loss and how many in the remaining accidents. It has also been described in chapter 4 how the risk of losing life can be calculated if it were to be assumed that fatalities occur only when the ship is lost or only when the ship is not lost. These two assumptions are the extremes of the possibilities to interpret the available accident data. In Table 21 the allowable reduction in the index R for these three ways to interpret the accident data are shown. It can be seen that the allowable reduction in the index R is much more if the fatalities would only occur when the ship is lost.

Table 21: The index A that results in an equivalent level of risk and the allowable reduction in the index R for different interpretations of the accident data.

	Fatalities occur evenly	Fatalities occur when ship is lost	Fatalities occur when ship is not lost
SALL	0.252	2.720	0.278
Risk of losing life	€ 1,577,000	€ 7,245,000	€ 997,000
A_{new}	0.525	0.347	0.543
Allowable reduction	-0.049	-0.227	-0.031
%	-8.6%	-39.5%	-5.4%

6.1.6. Total ship loss

The effect of total ship loss will be split in two. First the effect of taking the entire cost of the ship into account, instead of half, will be evaluated. This can also be seen as the worst case scenario where the ship has an accident just after it has been delivered. Second, the effect of lower wreck removal costs are evaluated. Therefore, the wreck removal costs will be taken equal to one time the newbuilding price, instead of two times.

In Table 22 the result can be seen. A ship that is twice as expensive reduces the allowable reduction in the index R with 12.2%. Taking only half the wreck removal cost into account increases the allowable reduction in the index R by 46.9%. This shows that it is important to establish a representative figure for the latter. This will be hard though, since the costs of wreck removal are very sensitive to the circumstances of the accident.

Table 22: The influence of the costs of total ship loss on the allowable reduction in the index R.

	Risk		Attained subdivision index	Allowable reduction
Original	€18,020,000	Manned	0.574	
		Unmanned	0.525	-0.049
More expensive ship	€20,074,000	Manned	0.574	
		Unmanned	0.531	-0.043
Lower wreck removal costs	€13,757,000	Manned	0.574	
		Unmanned	0.502	-0.072

6.2. Conclusion and further steps

The sensitivity study showed that only the cargo value, ship value and wreck removal costs have a significant influence on the outcome. Concerning the cargo value, it will be a matter of choice and design what kind of cargo the ship will be carrying. In case of a general cargo ship, choosing containers as cargo will lead to a more conservative conclusion, since the value of containers is relatively high.

The value of the ship has been taken as halfway its depreciation in this research. A more substantiated study on the average age of ships that are part of a collision or contact could improve the detail of the number that is used. The average age of ships that are part of a collision or contact might differ from half their lifetime. The assumption to use half the depreciation of their value might therefore be incorrect. If the extreme case would be taken where the newbuilding price of the ship is assumed, the outcome will change significantly. However, the change is likely to be in the order of two to five years. A more substantiated study would, therefore, not influence the outcome.

The wreck removal costs have a significant influence, but their values are hard to predict. A more substantiated study on the wreck removal costs related to ship size could lead to a better estimate. However, the uncertainty will remain high, since the costs will mostly depend on the circumstances of the accident instead of the size of the ship.

The accident data that is available for determining the risk of losing life is insufficient. Different interpretations of this data lead to different outcomes of the allowable reduction in the index R. Especially the difference for different ship types is noteworthy. Other interpretations of the accident data lead to a range of possible outcomes. In Table 23 these results are summarized. A minimal reduction of 5.5% can be expected and a maximum of 39.5%. However, the minimum is established with the extreme, unrealistic assumption that there are only lives lost when the ship is not lost. It can be expected that the allowable reduction in the index R will be over 8.6%.

Table 23: A summary of the range of allowable reduction in the index R for the 6,000 dwt general cargo ship.

	Expected reduction		Minimum reduction		Maximum reduction	
	[-]	[%]	[-]	[%]	[-]	[%]
6,000 dwt ship	-0.049	-8.6	-0.031	-5.5	-0.227	-39.5

The analysis of the 6,000 dwt ship shows that a reduction in the index R can be allowed for this ship when the principle of equivalent safety is used. In order to be able to derive a more general conclusion, two more ships will be evaluated. As was mentioned in paragraph 1.2, it is expected that the impact of removing the crew is higher for smaller ships. Therefore, it is expected that a higher reduction in the index R can be allowed for smaller ships. In order to confirm that for larger ships the effect is reduced, a ship that is around twice the size of the 6,000 dwt ship will be analysed. Also, it is expected that the transition to unmanned shipping will start with the smallest ships. Take for instance the projects of the YARA Birkelande and the ReVolt, which are designs of small container ships that can carry around 100 TEU (Kongsberg, 2017c; Tvete, n.d.). Therefore, an analysis will be conducted for a ship that is smaller than 6,000 dwt.

7. Risk analysis of a 4,000 dwt and a 13,000 dwt ship

In the previous chapter it was mentioned that a risk analysis will be conducted for two more ships. One ship that is less than 6,000 dwt and one ship that is about twice as big as 6,000 dwt. In this chapter, the two ships that will be analysed are presented first. Thereafter the numbers used for the consequences will be discussed. The results of the risk analysis will be presented next. Subsequently an evaluation of the results and a comparison of all three ships is given in order to evaluate the influence of the size of the ship on the risk profile and overall level of risk of the ship. Last, a conclusion is presented.

7.1. Ship selection

As for the ship of chapter 5, both ships in this chapter have been provided by DEKC Maritime. For convenience the ship of 6,000 dwt of the first risk analysis will be referred to as ship 1, the smaller ship of 4,000 dwt will be referred to as ship 2 and the larger ship of 13,000 dwt will be referred to as ship 3.

Ship 2 is a multipurpose general cargo ship. It has a length of 89.9 meters and size of 4,050 dwt. The amount of containers it could carry is 218 TEU. The ship is designed to have 10 crew on board. The newbuilding price is around €7 million, engineering and building costs included. A ship of this size has an index R of 0.444. The index A of this ship is 0.445, which is only slightly higher than the index R. The particulars of ship 2 can also be seen in Table 24.

Ship 3 is a container feeder. It has a length of 152.4 meters and size of 13,030 dwt. The amount of containers it can carry is 1,036 TEU. The ship is designed to have 18 crew on board. The newbuilding price is around €15 million, engineering and building costs included. A ship of this size has, with the current regulations, an index R of 0.579. However, the ship was built a few years before the current regulations were enforced. Therefore, the index A is lower than the index R and it is equal to 0.520. Also, the index A is determined by using only two drafts, the lightweight draft and summer draft, instead of three. Unfortunately DEKC Maritime does not have a more recent design of a similar sized dry cargo ship. The particulars of ship 3 can also be seen in Table 24.

Table 24: Particulars of ship 2 and 3 used in this study.

	Ship 2	**Ship 3**
Ship type	General cargo	Container feeder
Length	89.9 m	152.4 m
Lightweight	1503 t	5174 t
Steel weight	1020 t	3828 t
DWT	4050	13030
TEU	218	1036
Crew	10	18
Installed power	1500 kW	9000 kW
Fuel oil	308 t	1192 t
Lube oil	12 t	62 t
Newbuilding price	€7 million	€15 million
Required subdivision index	0.444	0.579
Attained subdivision index	0.445	0.520

The layout of ship 2 can be seen in Figure 11. The ship has only one cargo hold, the blue area. In the stern, the orange area, is the engine room. The orange area in the bow is the room of the bow thruster. The ship has a double hull and a double bottom with a width of 1.5 meters and a height of 1.2 meters respectively. The green tanks are ballast water tanks. The black-striped tanks are the fuel tanks. The function of the remaining spaces is not relevant for this research. The bulkhead deck is at 6.8 meters (in the layout this corresponds to the top of the green area). The spacing distance of the frames is 0.7 meters between frames 24 and 104. The remaining frames have a spacing of 0.6 meters.

The layout of ship 3 can be seen in Figure 12. The ship has three cargo holds, the blue areas. In the stern, the orange area, is the engine room. The orange area in the bow is the room of the bow thruster. The ship has a double hull and a double bottom with a width of 1.37 meters and a height of 1.5 meters respectively. The green tanks are ballast water tanks. The red tanks are the fuel tanks. The function of the remaining spaces is not relevant for this research. The bulkhead deck is at 9.5 meters (in the layout this corresponds to the top of the green area in the bow). The spacing distance of the frames is 0.78 meters.

7.2. Consequences of damage

In order to perform the risk analyses, the values of the consequences need to be known. In this paragraph the consequences related to ship 2 and 3 are described. The quantification of the consequences will be performed according to Table 4 in chapter 4 and by using the values presented in Table 24. As has been mentioned before, ship 3 will be evaluated in its lightest and deepest draft only, because the index A of this ship is determined with these two drafts only.

7.2.1. Loss of cargo

For ship 2 the maximum amount of containers it can carry is 218 TEU. The ship has only one cargo hold. In the lightest draft the ship will not carry any cargo and the value will be zero. In partial loading condition the value of the cargo is €5.2 million. In the deepest draft, the value of the cargo is €8.7 million.

For ship 3 the maximum amount of containers it can carry is 1,036 TEU. The ship has three cargo holds of which the middle cargo hold is slightly larger. The front and aft cargo hold have a capacity of 333 TEU and the middle cargo hold has a capacity of 370 TEU. This results in a value of the cargo in its deepest draft to be €13.3 million for the front and aft cargo hold and €14.8 million for the middle cargo hold.

7.2.2. Loss of fuel

Ship 2 has three fuel tanks with a combined capacity of 308 tonnes. The fuel tanks in the double hull have a size of 130 tonnes. The fuel tank in the stern has a size of 48 tonnes. Four situations will be considered. One situation for the damage of each tank individually and one situation for the damage of both tanks on portside. The clean-up costs for the small tank of 48 tonnes are equal to €622,000. The clean-up costs for the larger tanks of 130 tonnes are equal to €1.3 million. The clean-up costs for the combination of the tanks on portside with a total of 178 tonnes are equal to €1.6 million.

Ship 3 has four fuel tanks with a combined capacity of 1192 tonnes. The size of each tank is the same and equal to 298 tonnes. Only the tanks on one side can be damaged at the same time while the ship will not be lost. The scenario of damaging two tanks will be separated from the scenario where only one tank is damaged. The clean-up costs of one damaged fuel tank of 298 tonnes are equal to €2.3 million. The clean-up costs of two damaged fuel tanks of 596 tonnes in total are equal to €3.8 million.

7.2.3. Damaged machinery

The cost of the machinery will be estimated with the costs of the entire drive train. For ship 2 these costs are estimated by a value of €1.4 million. The clean-up costs of polluting liquids in the engine room will be incorporated in the costs of a damaged engine room. Ship 2 will need 12 tonnes of lube oil. An extra 3 tonnes is incorporated for any other spills. This results in a total clean-up costs of €270,000 and thus a total costs of damaged machinery of ship 2 of €1.6 million.

For ship 3 the costs of the drive train are estimated by a value of €5.6 million. Ship 3 needs 62 tonnes of lube oil. Clean-up costs for 80 tonnes of polluting liquids will be incorporated, which corresponds to €900,000. This results in a total clean-up costs of damaged machinery for ship 3 of €6.5 million.

7.2.4. Steel damage

The costs estimation of steel damage is considered in two parts. The costs related to dry-docking are taken as 3% of the newbuilding price. This means that the costs related to dry-docking for ship 2 will be equal to €210,000. For ship 3 these costs are equal to €450,000.

The variable costs are expressed in costs per meter of damage according to $€14{,}500 * \frac{steel\ weight}{ship\ length} * \frac{1}{8} * type$. For ship 2 this means that the variable costs are equal to $€21{,}000 * type$ per meter. For ship 3 this means that the variable costs are equal to $€45{,}000 * type$ per meter.

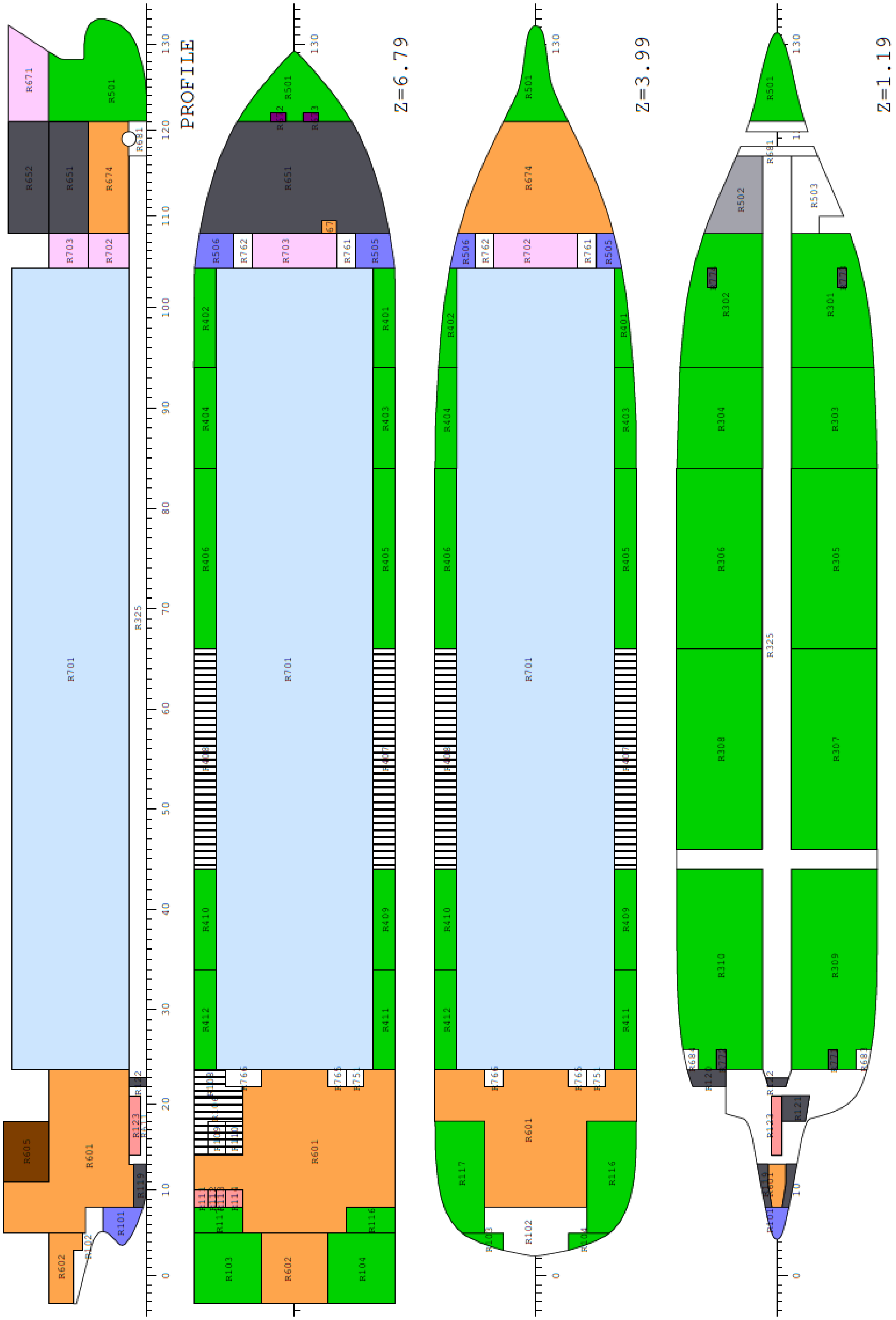

Figure 11: The layout of ship 2. The blue area is the cargo hold. The black-striped areas are fuel tanks. The green areas are ballast water tanks. The orange area in the stern is the engine room. The function of the remaining spaces is not relevant for this research. The scale in the length of the ship are the frames with a spacing of 0.7 meters between frame 24 and 104. The remaining frames have a spacing of 0.6 meters.

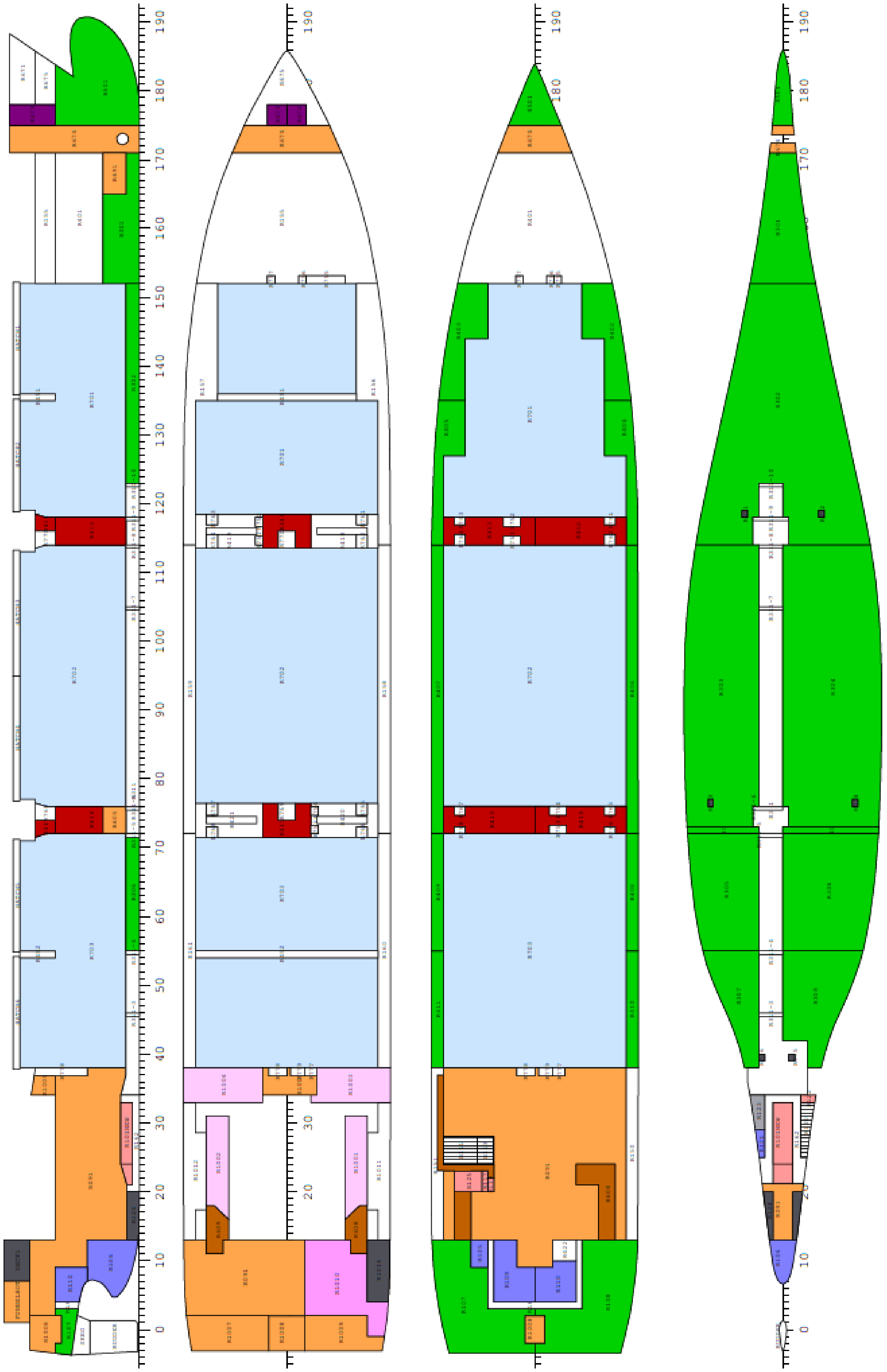

Figure 12: The layout of ship 3. The blue areas are the cargo holds. The orange area in the stern is the engine room. The red areas are fuel tanks. The green areas are ballast water tanks. The remaining coloured space are not relevant for this research. The scale in the length of the ship are the frames with a spacing of 0.78 meters.

7.2.5. Loss of life

As has been explained in chapter 4, the risk of losing life will be taken as €1,577,000 regardless of the type and size of ship. This number is calculated by taking the VPF of €6.25 million and multiply it with the SALL of 0.252 lives per accident.

7.2.6. Total ship loss

The costs of total ship loss consists of three parts: the value of the cargo it is carrying, the cost of the ship and the costs of wreck removal. Therefore, the costs of total ship loss will depend on the draft under consideration, since the amount of cargo carried will differ.

For ship 2 the costs of total ship loss in the lightest draft amount €17.6 million. In partial loading condition, the costs of total ship loss amount €22.9 million. In the deepest draft the costs of total ship loss amount €26.4 million.

For ship 3 the costs of total ship loss in the lightest draft amount €38 million. In the deepest draft the costs of total ship loss amount €79.4 million.

7.3. Results

In this paragraph the results of the risk analyses and the index A that will ensure an equivalent level of risk for the unmanned ship are presented. The calculations within the risk analyses are performed in the same manner as the first risk analysis as in paragraph 5.3, and they can be found in appendix C and D.

An overview of the risk profile of ship 2 is given in Table 25. The overall level of risk for ship 2 is equal to €15,502,000.

Removing loss of life from the risk profile results in a level of risk without crew of €13.9 million. This risk will be made equal to the risk of the manned ship 2 of €15.5 million. The result of this procedure is the risk profile of an unmanned version of ship 2 that is given in Table 26. For the unmanned ship to establish an equivalent level of risk, an index A of 0.378 would be needed. The reduction in the index A is 0.067 or 15.2% with respect to ship 2. Thus the allowable reduction in the index R for this ship is 15.2%.

Table 25: Overview of the risk profile and overall level of risk of ship 2.

Type	Risk	Probability
Loss of cargo	€ -	0.000
Loss of fuel	€ 174,000	0.161
Damaged machinery	€ 67,000	0.041
Steel damage	€ 206,000	0.445
Loss of life	€ 1,577,000	0.252
Total ship loss	€ 13,479,000	0.555
Overall level of risk	€ 15,502,000	
Attained subdivision index		0.445

Table 26: Overview of the risk profile and overall level of risk of the unmanned version of ship 2.

Type	Risk	Probability
Loss of cargo	€ -	0.000
Loss of fuel	€ 148,000	0.136
Damaged machinery	€ 56,000	0.035
Steel damage	€ 175,000	0.378
Loss of life	€ -	-
Total ship loss	€ 15,123,000	0.622
Overall level of risk	€ 15,502,000	
Attained subdivision index		0.378

An overview of the risk profile of ship 3 is given in Table 27. The overall level of risk for ship 3 is equal to €37,074,000.

Removing loss of life from the risk profile results in a level of risk without crew of €35.5 million. This risk will be made equal to the risk of the manned ship 3 of €37.1 million. The result of this procedure is the risk profile of an unmanned version of ship 3 that is given in Table 28. For the unmanned ship to establish an equivalent level of risk, an index A of 0.498 would be needed. The reduction in the index A is 0.022 or 4.4% with respect to ship 3. Thus the allowable reduction in the index R for this ship is 4.4%.

Table 27: Overview of the risk profile and overall level of risk of ship 3.

Type	Risk	Probability
Loss of cargo	€ 73,000	0.005
Loss of fuel	€ 60,000	0.026
Damaged machinery	€ 297,000	0.046
Steel damage	€ 904,000	0.520
Loss of life	€ 1,577,000	0.252
Total ship loss	€ 34,164,000	0.480
Overall level of risk	€ 37,074,000	
Attained subdivision index		0.520

Table 28: Overview of the risk profile and overall level of risk of an unmanned version of ship 3.

Type	Risk	Probability
Loss of cargo	€ 69,000	0.005
Loss of fuel	€ 58,000	0.025
Damaged machinery	€ 284,000	0.044
Steel damage	€ 864,000	0.498
Loss of life	€ -	-
Total ship loss	€ 35,799,000	0.502
Overall level of risk	€ 36,838,000	
Attained subdivision index		0.498

7.4. Evaluation of the results

In the previous paragraph the results of a risk analysis of two more ships were presented. In this paragraph these results will be evaluated and compared to the results of the risk analysis of ship 1. First the influence of the interpretation of the accident data is evaluated. Thereafter the risk profile of the three ships are compared in order to evaluate the influence of the size of the ship on the risk profile and the overall level of risk of the ship.

7.4.1. Influence of accident data on outcome

In chapter 6 the sensitivity of the result of the risk analysis of ship 1 has been evaluated. It was concluded that the accident data available for determining the risk of losing lives is insufficient. For ship 1 a range was provided of the allowable reduction in the index R based on different interpretations of the accident data. In Table 29 these results are repeated for comparison with ship 2 and 3. For ship 2 and 3 the differences in the allowable reduction in the index R also have been established. The results are presented in Table 30 and Table 31 respectively.

The risk analyses in this chapter and chapter 5 are performed assuming that fatalities occur evenly. From the results it can be seen that the bigger the ship, the smaller the allowable reduction in the index R is. For the smaller ships that fall under the SOLAS regulations, such as ship 2, the allowable reduction is about 15.2%. This decreases rapidly when the ship becomes bigger. For ship 1, which is only 50% bigger, the allowable reduction is only nearly half, namely 8.6%. For ship 3, which is about twice the size of ship 1, the allowable reduction is halved again, namely 4.4%.

If it would be assumed that the fatalities only occur when the ship is lost, the allowable reductions for all three ships increase five to six times. The risk of losing life increases with the same scale when the accident data is interpreted this way. However, the differences in allowable reduction in the index R for the different sizes in ship increases as well. The index R of ship 2 can be reduced with 90%, almost eliminating the requirement. For ship 1 the allowable reduction is large, namely 40%, but the remaining index R will still limit the design of the ship. For ship 3 the allowable reduction in the index R becomes large enough to have an impact on the design of the ship, when the data is interpreted in this way.

In general, it can be concluded that the allowable reduction in the index R will decrease when the ship becomes bigger. It will depend on the interpretation of the accident data at which ship size the allowable reduction is too small to cause a significant impact on the design

Table 29: The index A that results in an equivalent level of risk for ship 1 for different interpretations of the accident data.

	Fatalities occur evenly	Fatalities occur when ship is lost	Fatalities occur when ship is not lost
SALL	0.252	2.720	0.278
Risk of losing life	€ 1,577,000	€ 7,245,000	€ 997,000
A_{new}	0.525	0.347	0.543
Allowable reduction	-0.049	-0.227	-0.031
%	-8.6%	-39.5%	-5.4%

Table 30: The index A that results in an equivalent level of risk for ship 2 for different interpretations of the accident data.

	Fatalities occur evenly	Fatalities occur when ship is lost	Fatalities occur when ship is not lost
SALL	0.252	2.720	0.278
Risk of losing life	€ 1,577,000	€ 9,428,000	€ 774,000
A_{new}	0.377	0.041	0.412
Allowable reduction	-0.067	-0.404	-0.033
%	-15.2%	-90.9%	-7.5%

Table 31: The index A that results in an equivalent level of risk for ship 3 for different interpretations of the accident data.

	Fatalities occur evenly	Fatalities occur when ship is lost	Fatalities occur when ship is not lost
SALL	0.252	2.720	0.278
Risk of losing life	€ 1,577,000	€ 8,151,000	€ 904,000
A_{new}	0.497	0.402	0.507
Allowable reduction	-0.022	-0.118	-0.013
%	-4.4%	-22.8%	-2.5%

7.4.2. Comparison of the overall risk profile of the three ships

The risk profile of the three ships differs from each other. In Table 32 the overall risk profile for the three ships is presented. The ships are sorted from small to large from left to right. The percentage of contribution to the overall level of risk for each category is shown as well. It can be seen that the majority of the overall level of risk consists of the risk of a total ship loss.

Table 32: An overview of the risk profile and the overall level of risk of the three ships.

	Ship 2 – 4,000 dwt		**Ship 1 – 6,000 dwt**		**Ship 3 – 13,000 dwt**	
Loss of cargo	€ -	0.0%	€654,000	3.6%	€ 73,000	0.2%
Loss of fuel	€ 174,000	1.1%	€120,000	0.7%	€ 60,000	0.2%
Damaged machinery	€ 67,000	0.4%	€369,000	2.0%	€ 297,000	0.8%
Steel damage	€ 206,000	1.3%	€466,000	2.6%	€ 904,000	2.4%
Loss of life	€ 1,577,000	10.2%	€1,577,000	8.7%	€ 1,577,000	4.3%
Total ship loss	€ 13,479,000	87.0%	€14,835,000	82.4%	€ 34,164,000	92.1%
Overall level of risk	€ 15,502,000		€18,020,000		€ 37,074,000	
Attained subdivision index	0.445		0.574		0.520	

Another conclusion is that the overall level of risk increases when the ship increases. Apparently a higher risk is acceptable when the ship becomes larger. To show how this develops for even larger ships, an ocean liner named the Cosco Asia will be used in an example. A simple risk analysis of this ship would be to derive the risk of loss of ship and disregarding the remaining categories (see also Table 33). The value of the cargo is €402 million, based on the maximum number of TEU it can carry and the average value of a TEU of €40,000 (IHS Markit, 2017). The value of the ship is estimated by Frijters to be €253.5 million (Frijters, 2017). A ship with a length of 349 meters has an index R of 0.745 and thus a probability of ship loss of 0.255. This results in an estimate of the overall level of risk of €264.1 million. If the Cosco Asia would be required to have the same overall level of risk as ship 2, it would need to have an index R of 0.985. Acquiring such a high value is impracticable.

A way to compare the level of risk of different sizes of ships, is by using something like risk per TEU. In this way the transport capacity is incorporated in the evaluation of the overall level of risk of ships. There might be other factors that should be considered in the comparison of the overall level of risk of ships. Examples of these factors are miles travelled in busy waters, miles travelled in open sea, the size of the crew, the type of cargo, etc. Finding a method to compare the overall level of risk of different ships is recommended for further research.

Table 33: A simple estimation of the overall level of risk of the Cosco Asia

Length	349 m
TEU	10,050
Crew	34
Ship value	€253.5 million
Cargo value	€402 million
Required subdivision index	0.745
Estimated overall level of risk	€264.1 million

For the remaining categories (loss of cargo, loss of fuel, damaged machinery and steel damage), having only the results of three ships gives little insight in any trends that might occur. The details of the ships seem to have a significant influence on the values in the categories. For the risk analysis of ship 3 only two drafts were used. This causes for discrepancies in some of the categories. Especially for the risk of loss of cargo, where the risk is highest for the partially loaded draft (which is the draft that is not taken into account for ship 3). Also, its index A is lower than would be expected for such a ship with the current regulations, since it was designed under older regulations. This increases the risk of total ship loss. The opposite holds for the risk of total ship loss of ship 1. Since this ship is a concept design, the index A is higher than required to leave margin in the remaining design phases. This reduces the risk of total ship loss of ship 1.

Overall it can be expected that the risk of each category will increase if the size of the ship will increase. Only loss of life stays the same, since it is based on an average and it does not depend on the size of the crew. It cannot be concluded how each category will contribute to the overall level of risk based on the results in this research. However, the risk of total ship loss will remain to have the largest contribution.

7.5. Conclusions

In chapter 4 it has been discussed that the risk of losing lives depends on four uncertainties, which will be discussed next. In chapter 6 and paragraph 7.4 it has been shown that these uncertainties make it impossible to establish an exact allowable reduction in the index R at this point. These uncertainties will have to be investigated further before a substantiated conclusion can be drawn on the allowable reduction in the index R. After the discussion of the uncertainties a conclusion is presented on the allowable reduction in the index R that can be expected.

7.5.1. A difference in accident statistics for different ship types

First of all, there seems to be differences in the accident statistics for different ship types. There are significantly less fatalities related to bulk carriers and container ships compared to general cargo ships. These differences could be caused by differences in the average size of the ships per ship type or by differences in the average size of crew per ship type. Further investigation of these two possible explanations, as described next, should determine whether differences in the accident statistics for different ship types is still present. If so, it is recommended to evaluate differences in design and operation between the type of ships and how these could have an influence on the consequences of the accident, including the potential loss of life and the probability of survival.

7.5.2. The influence of ship size on risk of losing life

In the accident data there is no distinction between the sizes of the ships. Therefore, it is unknown what the influence of the size of the ship is on the risk of losing lives. The influence of a larger ship could be that the crew is less likely to be around the impact area during collision or contact, which reduces the risk of losing lives. Also, the probability of survival is higher for larger ships. If it will be more likely that fatalities will be present when the ship is lost, it might be expected that the risk of losing lives is higher for smaller ships. In order to establish a more substantiated allowable reduction in the index R, further investigation on the influence of a ships size on the risk of losing life is needed. Therefore, it is recommended to use the raw accident data and categorize the accidents per ship size. An evaluation of the data should indicate what the differences per ship size are and how they can be taken into account in a risk analysis.

7.5.3. The influence of crew size on risk of losing life

The sizes of the crew of the ships in the accident data is unknown. Combined with the lack of knowledge on the cause of fatalities, it has not been determined yet what the influence of the size of the crew is on the risk of losing lives. In the current analysis a statistical average loss of life per accident is used. To determine the actual risk for any crew member, the total number of people at risk needs to be known for the accidents that are evaluated. Furthermore, a further investigation is needed to establish what the actual influence of the size of the crew is on the risk of losing life. It is, therefore, recommended to evaluate the cause of fatalities related to collision. This evaluation will show whether lives were lost because the accident led to the loss of the entire crew, whether individual lives were lost for any reason or if any other significant reason for the loss of life can be found that has to be taken into account.

7.5.4. A discrepancy between the theoretical and actual probability of survival of ships

A fourth uncertainty is a discrepancy between the theoretical probability of survival of a ship, namely the index A, and the probability of survival that the accident data suggests. The index A suggests that at least 30% of all accidents should lead to a total ship loss. The accident data reveals that for general cargo ships around 10% leads to a total ship loss. For bulk carriers this is around 3% and for containerships no ship loss has been reported within the period of the accident data. The current risk analysis assumes that the index A is the best available approximation of the actual probability of survival. It should be further investigated why the theory differs from reality and whether a better approximation of the probability of survival would be needed.

The requirements concerning damage stability assume no interaction between the ship and the crew. In reality the crew will most probably do anything within their power to prevent the ship from sinking, although their options might be limited. Examples of these actions might be activation or placement of pumps to compensate the intake of water or stranding the ship on purpose. It is recommended to evaluate specific damage cases by establishing the specific damage to the ship and the corresponding probability of survival. If this probability does not correspond to the outcome of the accident, it should be mapped what the response of the crew was after the ship was damaged and how the response had any effect on the outcome of the accident.

7.5.5. Expected allowable reduction in the index R

In Table 34 the ranges of allowable reduction in the index R for all three ships are shown. The numbers in Table 34 have been used to compose Figure 13. In this figure, it has been assumed that the allowable reduction in the index R in percentages decreases linear with the ship length, using the percentages from Table 34. Therefore, Figure 13 can only be used as an indication of the range of the allowable reduction.

The results in Table 34 and Figure 13 are limited by assumptions based on the four uncertainties described above. First of all, it has been assumed that the index A is a valid method to establish the probability of survival of a ship, since no better alternative is available. Second, the average size of general cargo ships is lower than the average size of bulk carriers and containerships. Since the ships in this research have a size that is closest related to the size of general cargo ships, it has been assumed that the accident data of general cargo ships is best applicable. Third, since the influence of the size of the crew has not been established yet, the results do not take into account what the size of the crew of these ships is.

The expected allowable reduction in the index R is based on a fourth assumption. It is unknown what the cause of the fatalities is and thus it is unknown whether it is more likely to have an accident result in fatalities if the ship is lost or not lost. For the expected allowable reduction it is assumed that it is equally likely to have fatalities when the ship is lost as when the ship is not lost. The minimum allowable reduction has been established with the assumption that the fatalities occur only when the ship is not lost. The maximum allowable reduction has been established with the assumption that the fatalities occur only when the ship is lost.

Table 34: A summary of the ranges of allowable reduction in the index R for all three ships.

	Expected reduction		**Minimum reduction**		**Maximum reduction**	
	[-]	[%]	[-]	[%]	[-]	[%]
Ship 1 – 6,000 dwt	-0.049	-8.6	-0.031	-5.5	-0.227	-39.5
Ship 2 – 4,000 dwt	-0.067	-15.2	-0.033	-7.5	-0.404	-90.9
Ship 3 – 13,000 dwt	-0.022	-4.4	-0.013	-2.5	-0.118	-22.8

Overall, the index R is allowed to be reduced when the principle of equivalent level of risk is applied. However, the actual size of the reduction has yet to be determined because of uncertainties in the accident data. The allowable reduction in the index R is expected to decrease when the ship becomes larger. Figure 13 indicates the extent of the range of the allowable reduction in the index R. The figure also shows that the allowable reduction in the index R decreases when the ships become larger. However, Figure 13 has been based on the evaluation of only three ships. For a more general conclusion for the influence of ship size on the allowable reduction in the index R, more ships will have to be evaluated.

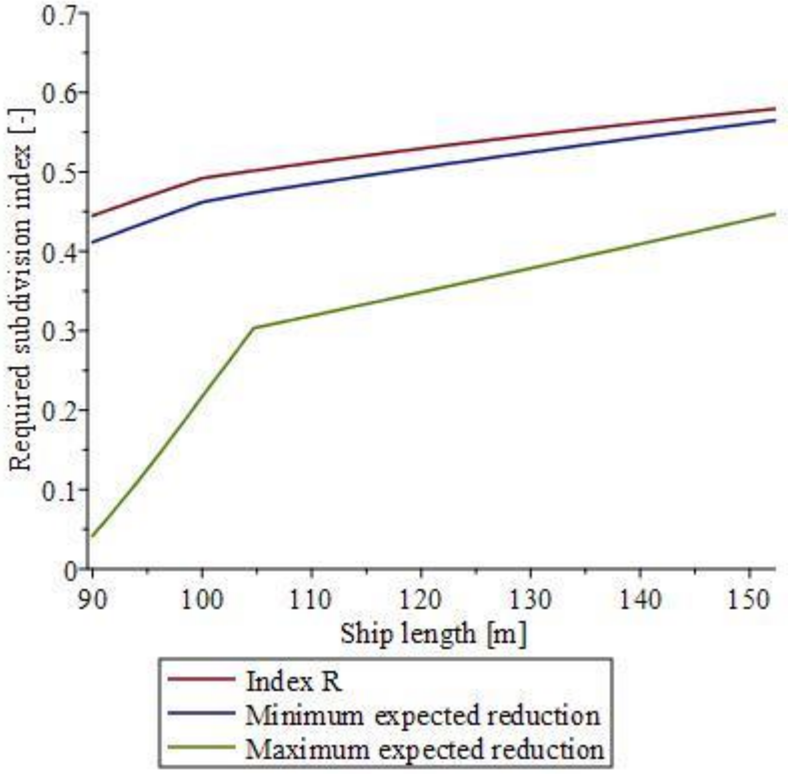

Figure 13: The range of the allowable reduction in the index R. The index R is the original required subdivision index from SOLAS. The minimum expected reduction uses the minimum reduction in percentages from Table 34. The maximum expected reduction uses the maximum reduction in percentages also from Table 34.

8. Advantages of a lower required subdivision index

In the previous chapter it has been concluded that it is uncertain what the allowable reduction in the index R will be for unmanned ships. An estimation of the allowable reduction has been made by making assumptions about the uncertainties. The estimation shows that the allowable reductions can be anywhere between no change and a reduction of 90%. In this chapter it will be discussed what the impact of reductions in the index R can be. Therefore, it will be discussed what the impact on the design can be if small reductions (0.05-0.10) in the index R are allowed. Next it will be discussed what can be expected if large reductions in the index R are allowed (over 50%). A third option is discussed thereafter: to sail with a lower value of GM, which will increase the transport capacity of the ship. Last, the impact that can be expected is evaluated in a conclusion. In this conclusion the impact is compared to the overall impact that can be expected if crew is removed as is proposed by Frijters (Frijters, 2017).

8.1. Small reductions in R, small changes in design

In chapter 7 it was concluded that at least small reductions in the order of 0.05 to 0.1 can be expected for smaller ships. A relative simple change in the design of a ship is the merging of two or more tanks. As an effect, the probability of survival for the damage cases that are related to these tanks will change, since more spaces will be flooded. Therefore, the index A of the ship will change.

Changing the layout of the ship will be sensitive to the specifics of the ship. It will be very unlikely that merging any two tanks in any ship will result in the same change in the index A. In order to demonstrate the possible impact of small reductions in the index R, ship 1 will be used as an example. The layout of ship 1 is shown in Figure 10 in chapter 5. First, the possible reduction of the number of tanks is established. Thereafter, the effects on the newbuilding price are discussed.

8.1.1. Reducing the number of tanks

In order to establish the possible effect of reducing the number of tanks in the ship on the index A, two changes in the layout of ship 1 are proposed. For both changes the index A has been recalculated and provided by DEKC Maritime.

The first proposed change is the merging of the three U-shaped tanks around the front cargo hold. This change in the layout results in a new index A of 0.514. This is 0.06 lower than the initial index A and thus within the bounds of what is considered to be a small change.

The second change that is proposed is the merging of the three double bottom tanks below the aft cargo hold. This change in the layout reduces the index A to 0.5139. This is only a minor change in the index A, but it does eliminate two tanks in the ship.

These two changes already show how different the impact of the merging of tanks can be. Merging the tanks in the bottom of the ship has only limited influence on the index A. Merging the side tanks of the ship has a noticeable effect, since the side tanks have the highest probability to be damaged.

The changes in the layout that are proposed in this paragraph can be improved with the right experience in ship design. With the right knowledge and experience it is expected that a naval architect will be able to halve the number of tanks in a ship when the ship is allowed to have an index A that is 0.1 lower. The effects on the newbuilding price when the number of tanks is halved will be discussed next.

8.1.2. Effects on newbuilding price

The number of tanks the ship is subdivided in has an influence on the building costs of the ship. The effects of halving the number of tanks in the ship can be found in five different categories. These categories are the following:

- **Amount of steel needed**
  Tanks and rooms are separated by bulkheads. If the number of tanks is reduced, the number of bulkheads and the required stiffeners are reduced. This results in a reduction in the amount of steel needed in the construction of the ship. If three of the U-shaped bulkheads around the cargo holds would be removed, the number of tanks in the ship are roughly halved. The total weight of these bulkheads is less than 1% of the steel weight of the ship.

- **Number of pumps and valves**
  Each tank needs a pump for the supply or drainage of water (DNV GL, 2016). Halving the number of tanks in the ship, means halving the number of pumps that need to be installed. To control the flow of air and water valves are needed (DNV GL, 2016). Halving the number of tanks in the ship will halve the number of valves in the ship as well.
- **Total length of piping**
  The pump of each tank needs pipes for the supply or drainage of water. Also, each tank needs an air pipe to equalize the pressure with the atmospheric pressure (DNV GL, 2016). Halving the number of tanks in the ship will therefor half the number of pipes in the ship associated with the tanks in the ship.
- **Man-hours needed for watertight fittings**
  All pipes in the ship need to go through watertight bulkheads that separate compartments. Reducing the number of pipes and the number of bulkheads will also reduce the number of watertight fittings. This will reduce the amount of man-hours needed for the fitting of the pipes in the ship.
- **Naval architect**
  The pipes and pumps have to be fitted in spaces in the ship which becomes a puzzle with small margins very fast. A reduction in the number of pipes and pumps reduces the work for the naval architect (H. Linskens, personal communication, 27 May 2019).

To find the effect on the newbuilding price, the newbuilding price will be evaluated using the method of Aalbers (Aalbers, n.d.). Aalbers provides a method to estimate the newbuilding price of the ship with basic parameters of the ship. In this way the known newbuilding price of ship 1 can be broken down into nine main groups. The definition of these groups is presented in Table 35. For each group it is indicated on which parameter it is based.

For each group Aalbers provides functions to estimate the material costs and required man-hours of the group. The contribution of each group to the newbuilding price of ship 1, according to these functions, can be seen in Figure 14. The total estimate of the newbuilding price with this method is €10.37 million. This is nearly the same as the provided newbuilding price of €10 million. However, an estimation of the costs for cargo systems is not provided. Since it is not expected that the reduction in the number of tanks has an influence on the costs of this group, the costs of the cargo systems are not incorporated in the evaluation.

Table 35: The breakdown structure of the newbuilding price of a ship according to Aalbers (Aalbers, n.d.).

Nr.	Group	Main Subsystems	Parameter
1	General & Engineering	Engineering, Planning, Production information, Transport, Scaffolding, Auxiliary constructions, Launching, Trials	Lightship weight
2	Hull & Conservation	Hull, Superstructures, Integrated tanks and foundations, Conservation	Steel weight
3	Ships Equipment	Steering System, Mooring System, Anti-rolling devices, Stores, Lifesaving &Fire f fighting Systems, Transport systems, HVAC, Stairs, Railings, Masts	Equipment weight
4	Accommodation	Outfitting, Carpentry, Inventory	Accommodation area
5	Electrical Systems	Switchboards, Automation, Lighting, Navigation and Communication, Cabling	Installed generator power
6	Propulsion & Power Systems	Propeller & Shaft, Reduction gear, Main Engine, Auxiliary Engines, Alternators, Boilers, Thrusters	Propulsion power
7	Systems for Propulsion & Power Systems	Fuel oil-, Lub.oil-, Cooling water Pumps, Compressors, Separators, Heaters, Coolers, Piping & Valves	Propulsion power
8	Bilge, Ballast & Sanitary Systems	Bilge/Ballast/FiFi pumps, Freshwater generator, Sewage plant, Piping & Valves	Hull numeral: $L * (B + D)$
9	Cargo Systems	Hatch covers, Deck cranes, Refrigeration plant, Side doors, Towing winch, Cargo pumping system	Cargo system weight

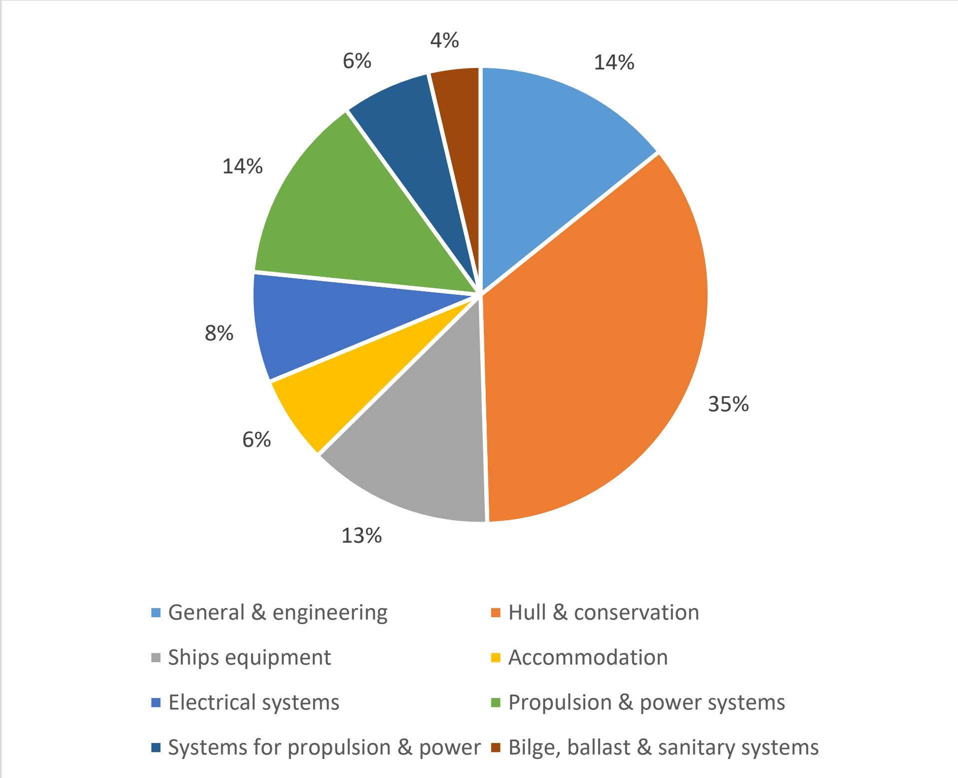

Figure 14: Breakdown of the newbuilding price of ship 1 by using the costs estimates provided by Aalbers (Aalbers, n.d.).

For each category described in the beginning of this paragraph the following effects on the newbuilding price can be expected:

- **Amount of steel needed**
  The groups *general & engineering* and *hull & conservation* will be effected by the reduction in the steel that is needed. These two groups together account for nearly half the newbuilding price. However, the weight on which these groups are based will only decrease with 1%. Therefore, the newbuilding price will decrease with only 0.5%.
- **Number of pumps and valves**
  The pumps and valves are accounted for in the *bilge, ballast & sanitary systems*, together with the pipes that are required. This group will be halved when the number of tanks will be halved. However, this is an overestimation of the cost reductions, since this group consists of more than just the pumps, valves and pipes for the tanks.
- **Total length of piping**
  The reduction in the total length of piping is accounted for by halving the costs of the group *bilge, ballast & sanitary systems* as described above under *number of pumps and valves*.
- **Man-hours needed for watertight fittings**
  The man-hours for construction work are incorporated in the group *hull & conservation.* The weight of the ship is reduced with only 1%. Therefore, a reduction in the man-hours for the total construction of the ship by 10% is expected to be an overestimation. However, if this overestimation would be taken into account, the newbuilding price will be reduced with 2.5%
- **Naval architect**
  The engineering of the ship by the naval architect is incorporated in *general & engineering.* However, only part of the works of the naval architect can be shortened and the naval architect is only part of the costs related to this group. The effect of this category is hard to estimate and it is expected to be low. Since the cost reduction for the category *man-hours needed for watertight fittings* is over estimated, the cost reduction for the naval architect will be incorporated in this estimation.

When the effects as described above are implemented, the newbuilding price of the ship is estimated by €9.87 million. Therefore, it can be expected that the newbuilding price of the ship can be reduced by 4.8% when the number of tanks in the ship is halved.

8.2. Large reductions in R, big changes in design

For the smaller ships that fall under SOLAS, as for ship 2, the maximum change that might be allowed is in the order of 90%. Such a significant change leads to the question, what the design of the unmanned ship will look like. In the case of such a low requirement, it would not be reasonable to base the changes in the design on the current design of a ship of the same size and type. If the index R is as low as only 10% of its original value, the entire ship design would have to be reconsidered.

Ships will become much simpler, when the layout is not limited by the index R. The location and number of tanks will no longer have to be chosen based on the value of the index A. Instead, the number and size of the tanks can be chosen, for instance, for optimal use of ballast water. The location of the ballast water and fuel tanks can subsequently be placed such that the cargo hold can be designed for optimal usage. A naval architect will have more freedom to make the most of the available space to transport cargo.

Although the design of the ship is expected to become simpler, a subdivision of the ship will still be present. The ship will still need at least a few different rooms, namely a cargo hold, an engine room, a bow thruster space, fuel tanks, some service space and probably some ballast tanks. It is not necessarily so that the flooding of one or more of these spaces will lead to the total loss of the ship. Therefore, the index A of the ship will probably still be larger than zero. An exercise of designing an unmanned ship without any restrictions will indicate what the expected minimum index A of an unmanned ship will be.

8.3. Allowed to sail with a lower value of GM

An option that is used to be able to comply with the index R is to restrict the value of GM the ship may sail with. Sailing with a higher GM results in more stability in general, and therefore also after the ship is damaged. If the stability of the ship is higher after it is damaged, its survivability is also higher. The increase of the value of GM that the ship is allowed to sail can be used to increase the index A. Vice versa, the decrease of the value of GM the ship is allowed to sail with can be used to decrease the index A. If the ship is allowed to sail with a lower value of GM, the ship will be able to carry more cargo.

The limit on the allowed value of GM appears to be imposed by the requirements concerning damage stability for most of the time (H. Linskens, personal communication, 27 May 2019). The minimum value of GM that is imposed by the requirements concerning damage stability will be different for every ship. For ship 1 the limit is set at a value of 0.5 meter, but for other ships this value may be larger to be able to achieve a high enough index A. In this paragraph the effect of sailing with a lower value of GM for ship 1 will be evaluated.

It can be mapped how much the index A for ship 1 will change if the GM is lowered. The calculations have been performed and provided by DEKC Maritime and are presented in Table 36. In this table the value of GM is lowered with steps of 0.05 meter. For each step the index A of the ship is provided. As can be seen, for small reductions in the index A (0.05-0.10) the value of GM can already be lowered to its overall minimum required value of 0.15 meter (IMO, 2008).

Table 36: The values of the index A for ship 1 for different values of the minimum required value of GM in partial and fully loaded loading conditions.

GM [m]	A [-]
0.50	0.574
0.45	0.561
0.40	0.557
0.35	0.550
0.30	0.543
0.25	0.528
0.20	0.517
0.15	0.489

In chapter 5 it was calculated that the allowable reduction in the index R is equal to 0.05 for ship 1. According to Table 36 this means that the value of GM can be lowered to 0.25 meter. A reduction like that means that about 15 TEU extra can be carried on this ship. That is an increase of 5% of the transport capacity compared to the transport capacity of the manned ship, which has a capacity of 300 TEU.
An increase in the transport capacity of 5% will increase the earning capacity of the ship by 5% as well. The earning capacity of the ship can be used as a tool to measure a ships performance and can be seen as the maximum a ship can earn in a certain period. The earning capacity depends on the transport capacity (how much cargo can it carry) and its speed (how fast the cargo is delivered).

Increasing the earning capacity does not necessarily mean that the ship will earn more. It will depend on the circumstances whether it will be beneficial. For instance, if there is no more cargo available for the route the ship is sailing, the ship cannot earn more. In that case it might be more beneficial to design a smaller ship. Another decision might be that the ship will decrease its speed, such that the earning capacity will remain the same. In that case the earnings of the ship are not affected, but the fuel consumption is decreased, and therefore the costs of operation.

Concluding, lowering the value of GM the ship is allowed to sail with could increase the transport capacity of the ship. The actual impact on the costs and earnings of the ship will be case specific and depends on the business case the ship is part of.

8.4. Conclusion

In this chapter it has been discussed what the impact of reductions in the index R could be. In general, changes in the design of a ship are case sensitive. For the best result, the unmanned ship should be designed from scratch after which it can be compared to the design of the manned ship for the same requirements. For small reductions in the index R (0.05 – 0.10), a case specific estimation can be made for the impact of the reductions. For larger reductions in the index R, a redesign of the ship will be necessary to evaluate the impact.

An evaluation of ship 1 showed that for an allowable decrease in the index A of 0.10, it can be expected that the number of tanks in the ship can be halved. This will decrease the steel weight of the ship, the number of pumps and valves needed and the total length of piping in the ship. Also, it is expected that the man-hours needed for construction will decrease as well as the work for the engineer. In total, it is expected that these effects will result in a reduction in the newbuilding price of the ship by 4.8%.

Another option is to lower the value of GM the ship is allowed to sail with. By reducing this limit, the ship will be able to carry more cargo. Ship 1 can carry 15 extra TEU if the value of GM is lowered from 0.50 meter to 0.25 meter. This reduction in the value of GM will reduce the index A of ship 1 by 0.05. The extra 15 TEU corresponds to a transport capacity increase of 5%. The impact of this increase depends on the business case the ship is part of.

In chapter 2 it was mentioned that in his thesis, Frijters describes which parts of the design are likely to change for unmanned ships (Frijters, 2017). He evaluated the influence on costs by removing crew and crew related equipment, including the bridge. Therefore, the cost reductions found in this research are an addition to the cost reductions found by Frijters.

Frijters realised estimations for a container feeder named the Deo Volente that is roughly the same size as ship 1. The particulars of this container feeder and of ship 1 are shown in Table 37. For this container feeder, he expects a reduction in lightweight of 8% and a reduction in electrical power generation of 6%. As a result he expects the building costs to decrease with 15% and the operational costs with roughly 45%. Therefore, he expects the total cost of ownership to be reduced by 35%. These numbers can also be seen in Table 38.

Table 37: The particulars of the Deo Volente that is evaluated by Frijters (Frijters, 2017) *and ship 1 that is used in this research.*

	Deo Volente	**Ship 1 – 6,000 dwt**
Ship type	General cargo	General cargo
Length	104.8 m	107.4 m
DWT	3,500 t	6,000 t
Lightweight	1,830 t	1,900 t
TEU	236	300
Crew	10	8
Newbuilding price	€12 million	€10 million

The cost reduction that is predicted by Frijters of 35% is significant. However, Frijters does not take into account the extra costs to realise unmanned shipping. Examples of extra costs mentioned by Frijters are the need of systems for situational awareness and a new mooring system, in order to eliminate the need of crew to throw lines to the quay.

The reduction in building costs as estimated in this chapter could further reduce the building costs as proposed by Frijters. Although the predicted 5% in this chapter is three times lower than the reduction of 15% as predicted by Frijters, it can contribute to the attractiveness and economic viability of unmanned ships. The MUNIN project predicts that the building costs of unmanned ships will become higher, taking the removal of the accommodation and crew related equipment and the installation of autonomous systems both into account (Kretschmann et al., 2015). Extra reductions in building costs, for instance by reducing the number of tanks in the ship, can contribute to overcome the higher building costs as predicted by MUNIN.

Table 38: The numbers of cost reduction as presented by Frijters for a container feeder (Deo Volente) (Frijters, 2017).

	Initial value	**Reduction according to Frijters**
Lightweight	1,830 t	155 t (8%)
Electrical power generation	2,510 kW	158 kW (6%)
Building costs	€12,000,000	€1,854,000 (15%)
Capital costs	€18,113,000	€2,830,000 (15%)
Operational cost	€48,170,000	€20,230,000 – €22,160,000 (42% – 46%)
Total cost of ownership	€66,283,000	€23,060,000 (35%)

9. Conclusions

The aim of this research is to find what reduction in the requirement concerning damage stability for unmanned ships can be allowed, if they are subjected to an equivalent level of risk as manned ships of the same size and type. In order to do so, the level of risk of three designs of manned ships has been determined. Subsequently it has been evaluated how the requirement for an unmanned version of these ships is allowed to be reduced while maintaining an equivalent level of risk.

The conclusion of this research is that a reduction in the required subdivision index is allowed when the principle of equivalent level of risk is applied. However, the actual size of the reduction cannot yet be determined. The determination of risk of losing life depends on the available accident data. Uncertainties in the available accident data have as a result that the risk of losing life cannot be determined accurately. Since the reduction in the required subdivision index directly relates to the size of the risk of losing life, the actual allowable reduction can only be speculated upon. The uncertainties in the accident data will be discussed next. The range of allowable reductions that can be expected is presented in paragraph 9.4.

First of all, for different ship types differences in the accident statistics are present. There are significantly less fatalities related to bulk carriers and container ships compared to general cargo ships. These differences could be caused by differences in the average size of the ships per ship type or by differences in the average size of crew per ship type. This leads to the next two uncertainties of the data.

In the accident data there is no distinction between the sizes of the ships. Therefore, it is unknown what the influence of the size of the ship is on the risk of losing lives. The influence of a larger ship could be that the crew is less likely to be around the impact area during collision or contact, which reduces the risk of losing lives. Also, the probability of survival is higher for larger ships. With this and the assumption that fatalities are more likely to be present when the ship is lost, it can be expected that the risk of losing lives is higher for smaller ships.

The size of the crew of the ships in the accident data is unknown, as well as the cause of fatalities. Therefore it has not yet been determined what the influence of the size of the crew is on the risk of losing lives. Also, it is unknown whether fatalities are more likely to occur when the ship is lost or when the ship is not lost.

A fourth uncertainty is a discrepancy between the theoretical probability of survival of a ship, namely the attained subdivision index, and the probability of survival that the accident data suggests. The attained subdivision index suggests that at least 30% of all accidents should lead to a total ship loss. The accident data reveals that for general cargo ships around 10% of the accidents leads to a total ship loss. For bulk carriers this is around 3% of the accidents and for containerships no ship loss has been reported within the period that is evaluated in the accident data.

In the next chapter the recommendations are described concerning these uncertainties. In the next paragraphs the sub-questions as presented in chapter 3 will be answered.

9.1. How can the level of risk of a (unmanned) sea going cargo ship be quantified?

Risk is defined as a measure of the likelihood that an undesirable event will occur together with a measure of the resulting consequence within a specified time. The undesirable events, their likelihood and their consequences, that lead to the overall level of risk are found by means of a risk analysis.

The elements that affect the damage stability-related risk are as follows. The undesirable events that lead to the overall level of risk are the damage cases that can be a result of collision or contact. Each damage case has a probability of occurrence, which can be taken as the likelihood of the undesirable event. The consequences of the damage cases are either a total ship loss or a combination of one of the following categories.

- Loss of cargo
- Loss of fuel
- Damaged machinery
- Steel damage
- Loss of life

A summary of the quantification of the consequences of the damage to the ship is given in Table 39. The probabilities of occurrence of the damage cases are defined in the International convention for the Safety of Life at Sea (SOLAS). The probability of survival of a certain damage case is also defined in SOLAS and this probability determines whether the damage case leads to a total ship loss or a combination of the other categories.

As was mentioned in the beginning of the conclusions, there are uncertainties related to the risk of losing lives. The total risk of losing lives as presented in Table 39 is established with three assumptions. The first being that the size of the crew has no influence on the risk of losing lives. The second assumption is that the accident data related to general cargo ships are the best representation for small ships, as those evaluated in this research. The average size of general cargo ships compares best with the size of the ships evaluated in this research. The third assumption is that the potential of losing life does not depend on whether the collision results in a total ship loss.

Table 39: An overview of the quantification of the consequences that are considered in the determination of the level of risk of sea going cargo ships.

Loss of cargo	Based on number of TEU's lost Cargo value: €40,000 per TEU
Loss of fuel	Based on volume of spilled fuel (V) in tonnes Clean-up costs: $€37{,}819 * V^{0.7233}$
Damaged machinery	Based on costs of drive-train and spills of polluting liquids (V_e) in tonnes Value: $€4{,}200 * (installed\ power\ in\ kW)^{0.79} + €37{,}819 * V_e^{0.7233}$
Steel damage	Consists of a constant part (docking) and a variable part (repairs) Docking costs: 3% of newbuilding price Repair costs per meter damage: $€14{,}500 * \frac{steel\ weight}{ship\ length} * \frac{1}{8} * Category$ Category 1: only outer hull penetrated; category 2: inner hull also penetrated
Loss of life	Total risk of losing lives: €1,577,000 regardless of the ship
Total ship loss	Cargo value: €40,000 per TEU carried Value of ship: halfway its depreciation Wreck removal: 200% of newbuilding price

9.2. What is the damage stability-related level of risk of a manned ship?

As can be seen in Table 39, the level of risk will depend on the size of the ship. In this research three ships of three different sizes are evaluated. Their risk profile and their overall level of risk are presented in Table 40. The main contributor to the overall level of risk is the risk of a total ship loss.

A sensitivity study showed that any reasonable alternatives in the values of the consequences of the first four categories of Table 40 do not affect the outcome significantly. Any changes in the values of the consequences of a total ship loss have a significant effect. Therefore, it is important that reasonable numbers are established for these values. Unfortunately, the costs of wreck removal depend for a great deal on the circumstances of the accident and a more substantiated cost estimation is not available.

Table 40: The risk profile and the overall level of risk of the three ships evaluated in this research.

	Ship 2 – 4,000 dwt		**Ship 1 – 6,000 dwt**		**Ship 3 – 13,000 dwt**	
Loss of cargo	€ -	0.0%	€654,000	3.6%	€ 73,000	0.2%
Loss of fuel	€ 174,000	1.1%	€120,000	0.7%	€ 60,000	0.2%
Damaged machinery	€ 67,000	0.4%	€369,000	2.0%	€ 297,000	0.8%
Steel damage	€ 206,000	1.3%	€466,000	2.6%	€ 904,000	2.4%
Loss of life	€ 1,577,000	10.2%	€1,577,000	8.7%	€ 1,577,000	4.3%
Loss of ship	€ 13,479,000	87.0%	€14,835,000	82.4%	€ 34,164,000	92.1%
Overall level of risk	€ 15,502,000		€18,020,000		€ 37,074,000	
Attained subdivision index	0.445		0.574		0.520	

9.3. How does the level of risk change if the crew is removed?

The overall level of risk of a ship changes with the amount of risk of losing lives if the crew is removed. In paragraph 9.1 the risk of losing lives has been presented as €1,577,000 regardless of the ship. This number has been established with assumptions which are also described in paragraph 9.1. In order to conclude that the overall level of risk will only change by the amount of risk of losing lives two more assumptions are made.

First, it is assumed that the probability of occurrence of the damage cases are relevant for unmanned ships as well. The probability of occurrence of the damage cases have been established based on accidents with manned ships. However, there is no better alternative available.

Second, it is assumed that the crew has no influence on the probability of survival of the ship in case of damage or on the consequences of the damage. These influences could be the activation of pumps to compensate the intake of water or by stranding the ship on purpose to prevent it from sinking. However, the possibilities of the crew are limited and the mentioned actions could be performed remotely as well.

9.4. What reduction in the required subdivision index can be allowed for an unmanned ship such that it will have the same level of risk as a similar manned ship?

An allowable reduction in the required subdivision index of the three ships evaluated in this research can be established when the assumptions as mentioned in paragraph 9.1 and 9.3 are taken into account. The expected allowable reduction under these assumptions is presented in Table 41. It can be expected that the potential of losing life might be larger if the collision would result in a total ship loss. If this would be the case, the allowable reduction in the required subdivision index can become larger. In the extreme case, where it is assumed that fatalities occur only if the ship is lost, the maximum allowable reduction is found. The minimum allowable reduction is found when the extreme case is assumed when all fatalities occur only if the ship is not lost. The minimum and maximum are also presented in Table 41.

Although the results in Table 41 depend on assumptions, it is expected that a reduction in the required subdivision index for an unmanned ship can be allowed. The actual size of the reduction has to be determined when the uncertainties mentioned in the beginning of this chapter have been further investigated.

Table 41: The allowable reduction in the required subdivision index for the three ships evaluated in this research. The expected reduction has been established with the assumptions mentioned in paragraph 9.1 and 9.3. The maximum reduction is established with the assumption that fatalities only occur when the accident results in a total ship loss.

	Expected reduction		**Minimum reduction**		**Maximum reduction**	
	[-]	[%]	[-]	[%]	[-]	[%]
Ship 1 – 6,000 dwt	-0.049	-8.6	-0.227	-39.5	-0.049	-8.6
Ship 2 – 4,000 dwt	-0.067	-15.2	-0.404	-90.9	-0.067	-15.2
Ship 3 – 13,000 dwt	-0.022	-4.4	-0.118	-22.8	-0.022	-4.4

9.5. What is the impact on the design when the ship is subjected to a lower required subdivision index?

In general, changes in the design of a ship are case sensitive. A case specific estimation is made to illustrate the quantification of the possible impacts. For the estimation, ship 1 has been evaluated for small reductions (0.05 – 0.10) in the required subdivision index. For an allowable reduction of 0.10, it can be expected that the number of tanks in the ship can be halved. This will decrease the steel weight of the ship, the number of pumps and valves needed and the total length of piping in the ship. Also, it is expected that the man-hours needed for construction will decrease as well as the work for the engineer. In total, it is expected that these effects will result in a reduction in the newbuilding price of the ship by 4.8%.

Another option is to lower the value of GM the ship is allowed to sail with. By reducing this limit, the ship will be able to carry more cargo. Ship 1 can carry 15 extra TEU if the value of GM is lowered from 0.50 meter to 0.25 meter. This reduction in the value of GM will reduce the index A of ship 1 by 0.05. The extra 15 TEU corresponds to a transport capacity increase of 5% and thus an increase of the earning capacity of the ship by 5%.

However, for the best result, the unmanned ship should be designed from scratch after which it can be compared to the design of the manned ship for the same requirements. Especially for larger reductions in the required subdivision index, this could lead to an even higher impact than described above.

10. Recommendations

There is a number of areas for which further investigation is recommended. These areas are sorted into three categories. First the recommendations for further investigation that is needed to improve the results of this research are discussed. Thereafter the recommendations that could follow the result of this research are discussed. Last, any other recommendations that are related to this research are discussed.

10.1. Recommendations for the continuation of this research

As has been mentioned in the conclusion, there are four uncertainties related to the result of this research. Further investigation in these areas is recommended in order to derive a substantiated and reliable result. For all recommendations in this paragraph it would be needed to gather raw data of accidents that have happened in the past.

10.1.1. Investigate discrepancy between theoretical and real probability of survival

There seems to be a discrepancy between the theoretical probability of survival and the probability of survival that can be derived from accident data. The theoretical probability of survival of a ship is equal to the attained subdivision index, and therefore it is expected that at least 30% of the accidents concerning collision or contact should lead to a total ship loss. From accident data it can be derived that only 10% or less of the accidents concerning sea going cargo ships lead to a total ship loss, depending on the type of ship. It should be further investigated why the theory differs from the reality and if there is influence from the crew on the survivability. Therefore, it is recommended to perform a study on cases of collision and contact. Within this study it should be derived what the theoretical probability of survival was after the ship was damaged. This should indicate whether all ships that should have been lost in theory actually were lost and whether all ships that should have survived in theory actually survived. Furthermore, it should be mapped what the response of the crew was after the ship was damaged and how the response had any effect on the outcome of the accident.

10.1.2. Closer investigation of the influence of ship size and type on accident statistics

The accident data that is available suggests that the potential loss of life depends on the type of ship. The loss of lives is significantly lower for bulk carriers and container ships than for general cargo ships. This could be the cause of the average size of the ships in each category. General cargo ships are generally smaller than bulk carriers and container ships. Further investigation on the influence of the size of the ship on the potential loss of life is needed. It is, therefore, recommended to collect data on the size of the ships in the accident data and on what size of ship a fatality occurred.

It may be possible that this investigation results in the conclusion that the potential loss of life still seems to depend on the type of ship. If that is the case, further investigation on the influence of the type of ship on the consequences of the accident is needed. It is, therefore, recommended to evaluate differences in design and operation between the type of ships and how these could have an influence on the consequences of the accident, including the potential loss of life and the probability of survival.

10.1.3. Closer investigation of cause of fatalities and influence of crew size

It is unknown what the size of the crew was of all ships in the accident data. It is, therefore, also unknown what the number of people at risk was. In the extreme case that there were as much people at risk as there were fatalities, it would mean that an accident would lead to the death of all crew. Secondly, it is unknown what the cause of the fatalities was. It could be that the fatalities are a result of a few cases were the entire crew was lost, independent of the size of the crew. It could also be that the possibility to lose any life depends on the crew size and that one or more fatalities are expected to happen sooner on ships with a larger crew. Therefore, it is recommended to further investigate the cause of the fatalities and the relation with the size of the crew of the ship.

10.2. Recommendations that follow this research

The results of this research can be used in further work. In this paragraph recommendations are made for research that can be conducted as a follow up.

10.2.1. Investigation of change in the probability of collision for unmanned ships

This research focusses on the events and consequences that assume that a ship is damaged as a result of collision or contact. The probability that a ship is part of a collision or contact is not taken into account. It may well be that the probability that a ship is part of a collision will change if the transition towards unmanned ships is made. If this probability decreases, an even lower survivability might be required. It is recommended to further investigate how the probability that a ship is part of a collision will change for unmanned ships.

Second the transition towards unmanned shipping will probably also have an effect on the type of damage that can be expected. Within this research the method to estimate the probability of occurrence of a certain damage for manned ships has been used. It is recommended to further investigate how these probabilities might change for unmanned ships. It is recommended to perform a hazard identification process. The hazard identification process should lead to a list of possible faults of the unmanned ship that could lead to collision or contact. For each fault it should be indicated what the (expected) probability of occurrence is and what the expected damage to the hull is.

10.2.2. Analysis of the risk profile of a larger selection of ships

The results of the current risk analyses are dependent on details of the ships under evaluation. Therefore, how the contribution of each category will develop for increasing size is uncertain. Furthermore, the actual development of the influence of the risk of losing lives on the overall level of risk is uncertain. It is recommended to perform the risk analysis as used in this research on a larger selection of ships. With the results of these risk analyses more substantiated and general conclusions can be composed about the contribution of each category of consequence, especially for the risk of losing lives.

10.2.3. Design of an unmanned ship without a required subdivision index

The increase in economic efficiency has only been described qualitatively in this research. The actual increase appears to depend on the details of the ship and a quantification can only be made for a specific case. To estimate the increase in economic efficiency with the most certainty, it would be needed to design the unmanned ship from scratch in order to use its full potential. It is recommended to perform the process of designing an unmanned ship to find the potential economic efficiency. The allowable reduction in the required subdivision index will be largest for smaller ships, thus it is recommended to perform the exercise on a small ship. It is also recommended to perform the exercise for a required subdivision index of zero to see what the effects will be. The attained subdivision index is a property of the ship and this exercise will show what the attained subdivision index of a ship will be if it is not required to have a certain value.

10.3. Further recommendations based on findings in this research

The recommendations in this paragraph follow from findings in this research. The performance of the corresponding research will lead to a more unambiguous comparison of manned and unmanned ships.

10.3.1. Establishing a method to compare the level of risk of different ships

Larger ships have a higher overall level of risk, but they also have a higher transport performance. In order to be able to compare the overall level of risk of every size of ship the transport capacity could be incorporated by establishing the risk per TEU carried or the risk per tonne carried. Other aspects might also be of influence on the acceptable overall level of risk. Examples of these aspects are the type of cargo carried, the size of the crew, the miles sailed in open sea or the miles sailed in busy waters. It is recommended to further investigate the aspects that should be taken into account in the comparison of the overall level of risk of different ships. It is recommended to derive a method to compare the overall level of risk of different ships.

10.3.2. Establishing better estimates for consequences of a collision

In section 4.2.3 the costs of the consequences of damage have been quantified. However, the following subjects need further investigation before they can be used in further research. First of all, the value of preventing a fatality (VPF) of €6,250,000 as is proposed by the EMSA (European Maritime Safety Agency, 2015c) is an updated value of the VPF. However, a range for the VPF is used for the remainder of the study, and therefore it appears that the accuracy of the proposed VPF is questionable. It is recommended to establish a single VPF which can be used in any future comparison between unmanned and manned ships.

Furthermore, the costs of wreck removal are case specific and an accurate estimate cannot be made. However, the current estimate of two times the newbuilding price can be improved. Further research on the costs of wreck removal can provide a better estimate of the costs of wreck removal. This research could indicate if the costs of wreck removal depend on the size of the ship. It is recommended to investigate former cases of wreck removal of different sizes of ships to come up with a more substantiated estimate of the average costs of wreck removal.

The non-fatal injury risks are not taken into account in this research, since the data on the possibility of injuries is scarce and not freely available. It is recommended to perform further research in this field in order to establish a substantiated method to incorporate these non-fatal injury risks in the risk analysis.

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Appendices

Appendix A: SOLAS evaluation

In this appendix the International Convention for the Safety of Life at Sea (SOLAS) will be evaluated. This evaluation aims to determine which requirements need to be or could be changed for unmanned ships. Furthermore, it will be indicated what the impact on the ship design of unmanned ships might be. The result can be used to determine which regulation(s) have the highest priority to be investigated for unmanned shipping. Either because of necessary changes to allow safe unmanned shipping, or because of the positive effect on economic efficiency.

For this evaluation, the consolidated edition of 2014 of SOLAS has been used. The amendments that have been approved since 2014 have been taken into account. SOLAS is divided into chapters, of which each covers a different subject. For each chapter, it is determined what amendments can be expected in order to incorporate unmanned ships. Second, the changes that are allowed within the ship design are highlighted. Last, the impact of these changes is indicated.

The results of the evaluation are described per chapter. The evaluation is summarized in Table 42. A conclusion is presented at the end.

Chapter I: General provisions

The general provisions is expected to remain relatively unchanged much for unmanned ships. Only a few changes are needed, mainly to acknowledge unmanned ships. Some definitions will need to be added and possibly some regulations have to be amended for unmanned ships. Overall, chapter I will remain to function with respect to unmanned ships and no consequences for the ship design are present.

Chapter II-1: Construction – Structure, subdivision and stability, machinery and electrical installations

The majority of chapter II-1 is expected to remain unchanged with only small amendments for unmanned ships. For example, the machinery and electrical installations on board will remain mostly the same for unmanned ships. A part of this chapter is dedicated to periodically unattended machinery spaces. This part will have to be amended such that autonomous systems are incorporated and unattended machinery is safely and reliably installed. The same holds for most construction requirements. These will have to be amended to take unmanned operations into account. For instance regarding the emergency towing arrangements and procedures. In the current regulations these procedures require crew to be operated.

There are three subjects of interest regarding changes in the design that might be allowed when crew is no longer present. First, spaces no longer have to be reached during sailing. Therefore, the doors and openings that are installed might change in location or means they are handled. The impact on the design depends on the difference between the current doors and openings and the change that is possible for unmanned ships.

Second, the intact stability will no longer have to take into account the safety of crew during the voyage. Stability will have to be sufficient to assure the ships operations and the safety of the cargo. Therefore, extra precautions for sufficient stability might no longer be necessary.

Third, the requirements concerning damage stability might be changed. This requirement is related to the risk of loss of lives, ship and cargo. Since the loss of lives is no longer present for unmanned ships, the overall level of risk is reduced. Subsequently, the requirements concerning damage stability might be relaxed, while still achieving an equivalent level of safety. This will have as an effect that more design freedom is created for the naval architect which allows for the opportunity to achieve more economic efficiency. The impact of these changes on the ship design of unmanned ships has the potential to be large.

Chapter II-2: Construction – Fire protection, fire detection and fire extinction

The second part of chapter II only focusses on the protection, detection and extinction of fire. It is the most extensive part of SOLAS. A lot of the regulations within this chapter require notification of crew and response from crew. Especially the later results in the need of a completely new designed firefighting system for unmanned ships. Therefore, the greater part of this chapter will need to be reviewed.

Further investigation of this chapter should determine the purpose of each regulation. All regulations will have to be amended such that interaction with humans on board is no longer necessary. The regulations that focuses on preventing the crew to be harmed should be considered to be taken out. For example, such a regulation could require that the fire spreading must be delayed in order for the crew to be able to get off safely, while in the end the ship and its cargo will be lost.

Also, similar to the requirements concerning damage stability, the risk of losing life will no longer be present. Therefore, some of the requirements might be relaxed, while still achieving an equivalent level of safety. Overall, this chapter has the potential to have a large impact on the design.

Chapter III: Life-saving appliances and arrangements

Chapter III aims to save lives in emergency situations. The presence of equipment is an example of the content of this chapter. Regarding unmanned ships, there will be no people on board that need to be saved in emergency situations. Therefore, the majority of this chapter can be eliminated for unmanned ships, but the impact on the design is expected to be small.

However, there is one subject that needs consideration regarding the saving of lives on sea. When an emergency arises on a nearby ship which has humans on board, does the unmanned ship need to have any means to assist in saving lives? If so, new requirements will have to be made in order to assure useful and practicable appliances and arrangements.

Chapter IV: Radiocommunications

The goal of chapter IV is to assure the ability of communication between the ship and others. This chapter assumes and/or states that there are humans on board who are able to work with the radio equipment. For unmanned ships, the regulations will have to be amended such that communication with an on shore control centre is feasible. The control centre must then be able to "communicate" with the ship. The change in radiocommunication is expected to have no impact on the design of the ship.

Chapter V: Safety of navigation

In chapter V regulations are set up to assure the safety of navigation. The chapter addresses multiple topics. For example, the information that should be available and how it should be obtained. Also, the operation and testing of the steering gear is covered, as well as the visibility from the bridge or the transfer of pilots on and off the ship. The ships' manning is also mentioned, such that it needs to be determined what the minimum safe manning is for the ship. These examples indicate that some of these regulations will remain the same with only little changes, for example the availability of information. Other will need more amendments or are not applicable at all. Overall, these regulations are expected to have no or only very little impact on the design of the ship. The part of ship design that is addressed in this chapter, is the bridge, which will no longer be needed for unmanned ships in its current form.

Chapter VI: Carriage of cargoes and oil fuels

This chapter is expected to hardly chance for unmanned ships. Although the design of the cargo holds (and similar) might chance if the design of unmanned ships is reconsidered, the cargo should still be stored in a safe manner. The main change that can be expected is that no humans can perform checks during the voyage. This could have a small influence on the ship design.

Chapter VII: Carriage of dangerous goods

In chapter VII the carriage of dangerous goods is addressed. The carriage of dangerous goods by unmanned ships still needs to happen in a safe manner. Therefore, this chapter is expected to hardly change. On change that can be expected is that the availability of documents will need to become digital, since no crew member can handover a hardcopy of the documents in the harbour.

Chapter VIII: Nuclear ships

Chapter VIII is not expected to change for unmanned ships. It is beyond the scope of this evaluation to determine whether unmanned nuclear ships are feasible. Changes in the regulations could be needed to ensure safe unmanned nuclear ships.

Chapter IX: Management for the safe operation of ships

Chapter IX is not expected to change for unmanned ships and has no influence on the ship design.

Chapter X: Safety measures for high-speed craft

Chapter X is not expected to change for unmanned ships and has no influence on the ship design. Furthermore, this chapter refers to another code. The impact of that code, specific for high speed craft, will not be taken into account in this evaluation.

Chapter XI-1: Special measures to enhance maritime safety

Chapter XI-1 is not expected to change for unmanned ships and has no influence on the ship design.

Chapter XI-2: Special measures to enhance maritime security

For chapter XI-2, amendments are needed in order to incorporate unmanned ships. The content of these changes, however, will not have an influence on the ship design.

Chapter XII: Additional safety measures for bulk carriers

Chapter XII is only applicable for bulk carriers. The main purpose of this chapter is to make sure that if one cargo hold is damaged, and it is flooded with water, the ship will not sink. This accounts both for the stability of the ship and the structural strength of the cargo hold. Safety analyses might show that an unmanned ship can accept a higher probability of failure, while still achieving the same level of risk, since the risk of losing life will not be present. However, the safety of the cargo is still of importance and changing this chapter will have a large impact on the risk the ship is subjected to. Therefore, it does not seem likely that this chapter will change much for unmanned ships.

Chapter XIII: Verification of compliance

Chapter XIII is not expected to change for unmanned ships and has no influence on the ship design.

Chapter XIV: Safety measures for ships operating in polar waters

Chapter XIV is not expected to change for unmanned ships and has no influence on the ship design. Furthermore, this chapter refers to another code. The impact of that code, specific for polar waters, will not be taken into account in this evaluation.

Table 42: A summary of the evaluation of SOLAS per chapter. In order to incorporate unmanned ships, the regulations within SOLAS might need amendments. The amendments could allow changes in the ship design. The goal of the evaluation is to find the amendments that have the biggest impact on the ship design.

Chapter	Changes of regulations	Change of ship design	Impact on design
I: General provisions	Few adaptions needed	None	None
II-1: Construction – Structure, subdivision and stability, machinery and electrical installations	Adaptions to assure unmanned procedures. Adaptions for safe unmanned mechanical and electrical installations. Changes in the stability requirements that ensure safe operations (since the crew is no longer part of the operations).	Damage stability and watertight layout. Intact stability. Doors and openings within structure.	Large
II-2: Construction – Fire protection, fire detection and fire extinction	Needs careful consideration and major adaptions, such that no interactions with and response from the crew is required.	New integrated fire system needed. Structural design might be allowed to change.	Large
III: Life-saving appliances and arrangements	This chapter has in its current state no application on unmanned ships	Remove all equipment and arrangements	Small
IV: Radiocommunications	The chapter needs to be amended such that communication with the ship takes into account that there are no humans on board. The humans involved will be in an on shore control centre.	None	None
V: Safety of navigation	Amendments are needed in order to assure the safety of navigation for a ship that is controlled by a machine or remotely.	Remove bridge, possibly replaced by a mast. Remove pilot transfer arrangements.	Very small
VI: Carriage of cargoes and oil fuels	Few adaptions needed	Possible change in cargo holds	Small
VII: Carriage of dangerous goods	Few adaptions needed	None	None
VIII: Nuclear ships	None	Unknown	Unknown
IX: Management for the safe operation of ships	None	None	None
X: Safety measures for high-speed craft	None	None	None
XI-1: Special measures to enhance maritime safety	None	None	None
XI-2: Special measures to enhance maritime security	Few adaptions needed	None	None
XII: Additional safety measures for bulk carriers	None (Only otherwise if safety analyses indicate that higher risks are acceptable)	Probably none	Probably none
XIII: Verification of compliance	None	None	None
XIV: Safety measures for ships operating in polar waters	None	None	None

Conclusion

The aim of the evaluation of SOLAS was to determine which requirements need to be or could be changed for unmanned ships to indicated what the impact on the ship design of unmanned ships might be. A summary of the evaluation is presented in Table 42.

The evaluation shows that the largest impact can be expected to be found in *Chapter II – Structure*. The chapter is divided into two parts. The first part concerns a variety of requirements involving the structure in general, among which damage stability is the most interesting subject. The second part is about the protection, detection and extinction of fire.

Concerning chapter II-2, the firefighting system will need changes since the current regulations assume that crew is present. A part of the assumptions concern the alarm system that informs the crew of the fire or the use of materials that slow down the fire in order to protect the crew. The regulations also indicate that the crew must be able to interfere and extinguish the fire. Therefore, a new system will need to be developed that can be remotely operated. However, there is only little prospect of creating more design freedom, concerning the firefighting system.

The requirements concerning damage stability do not necessarily have to change. If the requirements concerning damage stability do not change, the unmanned ship will be as least as safe as the conventional ship. The reason that it would be interesting to find out whether the requirements concerning damage stability can be changed, is because it is one of the first to limit the design freedom for a naval architect (H. Linskens, personal communication, 9 January 2019). The requirement might be relaxed, while still maintaining an equivalent safety level, since the risk of loss of life is no longer present.

Appendix C: calculations of each risk category of ship 2

In chapter 7 a risk analysis is conducted for a ship of 4,000 dwt indicated by ship 2. The particulars of ship 2 are described in chapter 7, as well as the quantification of the consequences for ship 2. The calculations of the risk per category are presented in this appendix.

Loss of cargo

Cargo will be lost when the blue area in Figure 11 in chapter 7 is penetrated, while the ship remains afloat. This results in the risk calculation that is presented in Table 43. For ship 2, there is no risk of losing cargo. If there is cargo in the cargo hold, the probability that the ship will survive a damage case where the cargo hold is damaged is equal to zero.

Table 43: Calculation of the risk of losing cargo for ship 2.

Draft		**Cargohold**
d_l	Probability	0.235
	TEU	0
	Cargo value	€ -
	Risk	€ -
d_p	Probability	0.000
	TEU	131
	Cargo value	€5.2 m
	Risk	€ -
d_s	Probability	0.000
	TEU	218
	Cargo value	€8.7 m
	Risk	€ -
Total	Risk	€ -
	Probability	0.000

Loss of fuel

Fuel will be lost when the fuel tanks are penetrated, which are the striped areas in Figure 11 in chapter 7, while the ship remains afloat. This results in the risk calculation that is presented in Table 44. The total risk of losing fuel for ship 2 is equal to €174,000 with a probability of 0.161.

Table 44: Calculation of the risk of losing fuel for ship 2.

Draft		Fuel tank aft PS	Fuel tank front PS	Both PS	Fuel tank SB	Combined
d_l	Probability	0.087	0.154	0.001	0.155	
	Tank size	48	130	178	130	
	Costs	€622,000	€1.3 m	€1.6 m	€1.3 m	
	Risk	€54,000	€197,000	€2,000	€198,000	
d_p	Probability	0.071	0.060	0.000	0.061	
	Tank size	48	130	178	130	
	Costs	€622,000	€1.3 m	€1.6 m	€1.3 m	
	Risk	€44,000	€77,000	€ -	€78,000	
d_s	Probability	0.007	0.000	0.000	0.005	
	Tank size	48	130	178	130	
	Costs	€622,000	€1.3 m	€1.6 m	€1.3 m	
	Risk	€4,000	€ -	€ -	€6,000	
Total	Risk	€30,000	€70,000	€ -	€73,000	€174,000
	Probability	0.048	0.055	0.000	0.057	0.161

Damaged machinery

The machinery will be damaged when the engine room is penetrated, while the ship remains afloat. The engine room is the orange area in the aft part of the ship in Figure 11 in chapter 7. This results in the risk calculation that is presented in Table 45. The total risk of damaged machinery for ship 2 is equal to €67,000 with a probability of 0.041.

Table 45: Calculation of the risk of damaged machinery for ship 2.

Draft		
d_l	Probability	0.076
	ER value	€1.6 m
	Risk	€124,000
d_p	Probability	0.063
	ER value	€1.6 m
	Risk	€103,000
d_s	Probability	0.001
	ER value	€1.6 m
	Risk	€2,000
Total	Risk	€67,000
	Probability	0.041

Steel damage

Every damage case where the ship remains afloat will have steel damage as a consequence. This results in the risk calculation that is presented in Table 46. The total risk of steel damage for ship 2 is equal to €206,000 with a probability of 0.445 (equal to the index A of ship 2).

Table 46: Calculation of the risk of steel damage for ship 2.

Draft		
d_l	Probability	0.756
	Risk	€400,000
d_p	Probability	0.484
	Risk	€213,000
d_s	Probability	0.251
	Risk	€102,000
Total	Risk	€206,000
	Probability	0.445

Loss of life

As has been explained in chapter 4, the risk of losing life will be taken as €1,577,000 regardless of the type and size of ship. This number is calculated by taking the value of preventing a fatality (VPF) of €6.25 million and multiply it with the statistical average loss of life (SALL) of 0.252 lives per accident.

Total ship loss

The probability that the ship is lost is exactly the complement of the index A for each draft. This results in the risk calculation that is presented in Table 47. The risk of total ship loss for ship 2 is equal to €13,479,000 with a probability of 0.555.

Table 47: Calculation of the risk of total ship loss for ship 2.

Draft		
d_l	A	0.756
	$1-A$	0.244
	Value	€17.6 m
	Risk	€4,300,000
d_p	A	0.484
	$1-A$	0.516
	Value	€22.9 m
	Risk	€ 12,796,000
d_s	A	0.251
	$1-A$	0.749
	Value	€26.4 m
	Risk	€19,751,000
Total	A	0.445
	$1-A$	0.555
	Risk	€13,479,000

Appendix D: calculations of each risk category of ship 3

In Chapter 7 a risk analysis is conducted for a ship of 13,000 dwt indicated by ship 3. The particulars of ship 3 are described in chapter 7, as well as the quantification of the consequences for ship 3. The calculations of the risk per category are presented in this appendix.

Loss of cargo

Cargo will be lost when one of the blue areas in Figure 12 in chapter 7 is penetrated, while the ship remains afloat. This results in the risk calculation that is presented in Table 48. The total risk of losing cargo for ship 3 is equal to €73,000 with a probability of 0.005.

Table 48: calculation of the risk of loss of cargo for ship 3.

Draft		Cargohold aft	Cargohold middle	Cargohold front	Combined
d_l	Probability	0.063	0.134	0.159	
	TEU	0	0	0	
	Cargo value	€ -	€ -	€ -	
	Risk	€ -	€ -	€ -	
d_s	Probability	0.000	0.000	0.011	
	TEU	333	370	333	
	Cargo value	€13.3 m	€14.8 m	€13.3 m	
	Risk	€ -	€ -	€ 145,000	
Total	Risk	€ -	€ -	€73,000	€73,000
	Probability	0.000	0.000	0.005	0.005

Loss of fuel

Fuel will be lost when the fuel tanks are penetrated, which are the red areas in Figure 12 in chapter 7, while the ship remains afloat. This results in the risk calculation that is presented in Table 49. The total risk of losing fuel for ship 3 is equal to €60,000 with a probability of 0.026.

Table 49: Calculation of the risk of losing fuel for ship 3.

Draft		Fuel tank aft	Fuel tank front	Both	Combined
d_l	Probability	0.017	0.035	0.000	
	Tank size	298	298	596	
	Costs	€2.3 m	€2.3 m	€3.8 m	
	Risk	€39,000	€82,000	€ -	
d_s	Probability	0.000	0.000	0.000	
	Tank size	298	298	596	
	Costs	€2.3 m	€2.3 m	€3.8 m	
	Risk	€ -	€ -	€ -	
Total	Risk	€19,000	€41,000	€ -	€60,000
	Probability	0.008	0.018	0.000	0.026

Damaged machinery

The machinery will be damaged when the engine room is penetrated, while the ship remains afloat. The engine room is the orange area in the aft part of the ship in Figure 12 in chapter 7. This results in the risk calculation that is presented in Table 50. The total risk of damaged machinery for ship 3 is equal to €297,000 with a probability of 0.046.

Table 50: Calculation of the risk of damaged machinery for ship 3.

Draft		
d_l	Probability	0.082
	ER value	€6.5 m
	Risk	€532,000
d_s	Probability	0.009
	ER value	€6.5 m
	Risk	€61,000
Total	Risk	€297,000
	Probability	0.046

Steel damage

Every damage case where the ship remains afloat will have steel damage as a consequence. This results in the risk calculation that is presented in Table 51. The total risk of steel damage for ship 3 is equal to €904,000 with a probability of 0.520 (equal to the index A of ship 3).

Table 51: Calculation of the risk of steel damage for ship 3.

Draft		
d_l	Probability	0.811
	Risk	€1,517,000
d_s	Probability	0.230
	Risk	€290,000
Total	Risk	€904,000
	Probability	0.520

Loss of life

As has been explained in chapter 4, the risk of losing life will be taken as €1,577,000 regardless of the type and size of ship. This number is calculated by taking the value of preventing a fatality (VPF) of €6.25 million and multiply it with the statistical average loss of life (SALL) of 0.252 lives per accident.

Total ship loss

The probability that the ship is lost is exactly the complement of the index A for each draft. This results in the risk calculation that is presented in Table 52. The risk of total ship loss for ship 3 is equal to €34,164,000 with a probability of 0.480.

Table 52: Calculation of the risk of total ship loss for ship 3.

Draft		
d_l	A	0.811
	$1 - A$	0.189
	Value	€38 m
	Risk	€7,199,000
d_s	A	0.230
	$1 - A$	0.770
	Value	€79.4 m
	Risk	€61,128,000
Total	A	0.520
	$1 - A$	0.480
	Risk	€34,164,000