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Quantification of the risk reduction potential of autonomous navigation

Jiri de Vos[1], Jeroen Pruyn[1] and Robert Hekkenberg[1]

ABSTRACT

Autonomous ships have become a topic of interest for an increasing number of researchers over the last few years. Most of the research that is being performed focuses on autonomous navigation. An important driver for this research is the belief that autonomous navigation will increase safety at sea. In order to evaluate the possible safety benefit of autonomous navigation, it is essential to have an understanding of the risk associated with navigation-related accidents. In this paper, a monetary quantification of the risk associated with navigation-related accidents will be presented, to support designers in determining the acceptable costs of an autonomous navigation system.. It is the intention to provide order-of-magnitude figures for the annual risk for different ship types and sizes. Although it is acknowledged that the analysis comes with uncertainties, the results provide an overview contribution that different damage cases make to the overall risk per year, associated with navigation-related accidents. It is found that the annual risk can be expected to be between €1.5 billion and €2.5 billion, or a €45k to €75k risk per vessel per year. Consequently, the maximum annual safety benefit of autonomous navigation is equal to this figure if autonomous navigation will be able to prevent all navigation-related accidents.

KEY WORDS

Risk analysis; Navigation-related accidents; Safety at sea; Autonomous Navigation; Autonomy benefits.

INTRODUCTION

Over the last years, autonomous ships have become one of the most trending topics for maritime research. The MUNIN project (MUNIN, 2016), the AAWA project (Rolls-Royce, 2016), the YARA Birkeland demonstrator (Kongsberg, 2017), the REVOLT (Tvete, 2015) and the Design For Value (D4V) project (DIMECC, 2018) are examples of projects that investigate the feasibility of autonomous ships. Besides these explorative projects, a large portion of the research that is being performed focuses on autonomous navigation. The primary aspects of autonomous navigation are route planning and collision avoidance. Among others, Beser & Yildirim (2018), Huang et al. (2020) and Ramos et al. (2019) focus on these aspects.
An important driver for the research on autonomous navigation is the belief that this will increase safety at sea. Several studies attribute the cause of 60-90% of the accidents to a human error, with navigation-related accidents (i.e. collision, contact and stranding) at the high end of the spectrum (EMSA, 2019; Rothblum, 2000; Wróbel et al., 2017). As a result, it is expected that the number of accidents will go down if autonomous ships are introduced (Wróbel et al., 2017). For a designer or client contemplating the option of autonomous navigation, the potential benefits are the avoidance of these collisions. However, such benefits have not been quantified specifically yet.

In order to have a better understanding of the effect of a reduction in navigation-related accidents on safety at sea, the concept of safety must be understood. Safety is defined by the IMO as "Safety is the absence of unacceptable levels of risk (…)" (IMO, 2013). Therefore, it is essential to have an understanding of the current risk associated with navigation-related accidents. Subsequently, the safety benefit can be expressed as the amount of risk that will be avoided. In earlier work, we have already estimated the possible safety benefit of the introduction of autonomous ships (de Vos, Hekkenberg, & Valdez Banda, 2020). However, in the previous analysis, the risk associated with navigation-related accidents was represented by the number of ships lost and the number of lives lost for all ship types and sizes. With this more general interpretation, the designer is not able to quantify the benefits and compare them to the costs of the autonomous navigation systems.

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In this paper, a more quantitative risk analysis of navigation-related accidents is presented. The result is an estimation of the annual risk associated with navigation-related accidents expressed in monetary terms. Within the analysis, a distinction will be made between various ship types and sizes. Furthermore, the estimated annual risk will consider both the consequences when the ship will be lost due to the accident and the consequences when the ship will not be lost due to the accident.
The estimates of the cost of the consequences and the probability of occurrence of these consequences come with uncertainties. The cost associated with an accident is highly dependent on the specific details of the accident and the ships that are involved. Consequently, the numbers in this paper shall be interpreted as rough estimates. It is the intention to provide a ballpark figure of the annual risk and to be able to evaluate the potential risk reduction achieved by autonomous navigation and the distribution of this risk reduction over ship types and sizes.

The next section describes how the risk analysis of navigation-related accidents is performed. In the following section, the determination of the probability of occurrence of the most important consequences and their associated cost are presented. The results of the risk analysis, as well as a discussion on the results, are presented next. A summary of the results and the conclusions are presented in the last section.

METHOD

Before finding the annual risk associated with navigation-related accidents, a definition of risk will be given. Risk is defined by IMO as "a measure of the likelihood that an undesirable event will occur together with a measure of the resulting consequence within a specified time" (IMO, 2013). In other words, risk consists of two independent parts, probability and consequence. The probability is generally expressed as a probability per unit of time, for example per year. The consequences of the event can be of different natures. For instance, the loss of human lives cannot directly be compared to a financial loss like the loss of cargo or damage to the ship. However, using the concept of the value of preventing a fatality (VPF), estimating the value of the lost cargo, and approximating the cost of required repairs to the ship, removal of a wreck and/or cleaning up spills, all consequences can be expressed as monetary values.

As a result, the approximate annual risk associated with navigation-related accidents can be found when the five steps presented below are performed. More details on these steps can be found hereafter.

1. Determine the number of accidents per year.
2. Define the most important categories of consequences and their probability of occurrence.
3. Establish the cost associated with each category of consequences.
4. Per category, multiply the cost of the consequences with the probability of occurrence per accident and the number of accidents.
5. Add the risks per category to find the overall annual risk.

The risk analysis is limited to cargo ships since the authors expect that these ships are the first to become autonomous (de Vos, Hekkenberg, & Valdez Banda, 2020). The ships are divided into five categories, using the StatCode 5 ship type coding system as is used by IHS Markit. The resulting five categories are General Cargo Ships, Bulk Carriers, Container Ships, Tankers and Other Cargo Ships.

Furthermore, a distinction will be made in ship size using ship length as a measure. A previous analysis by the authors showed that there are important differences in the consequences of an accident depending on the ship length (de Vos, Hekkenberg, & Valdez Banda, 2020).

The first step of the analysis consists of a casualty analysis. The IHS SeaWeb® database is used for the analysis of casualty data. The casualty data consists of all serious accidents concerning cargo ships from 2000 to 2018. Serious accidents are defined by IHS Markit as those accidents where the vessel incurred significant damage and/or was withdrawn from service. The most expensive accidents in terms of material damage are by definition serious accidents, and 99% of all lives lost are allocated to serious accidents as well. Consequently, we believe that limiting the analysis to serious accidents, thus not taking small incidents into account, is an acceptable limitation of the scope of the analysis. Therefore, the non-serious accidents are excluded from the analysis.

The casualties in the IHS SeaWeb® database are subdivided into eight categories: collision, contact, stranded, fire/explosion, foundered, hull/machinery damage, missing and war-loss/hostilities. For the analysis in this paper we only focus on navigation-related accidents, and, therefore, only the categories 'collision', 'contact' and 'stranded' are considered. The definitions of these categories as provided by IHS Markit are as follows:

- Collisions: Incident as a result of striking or being struck by another ship, regardless of whether underway, anchored or moored. This category includes collision with drilling rigs/platforms, regardless of whether in a fixed position or in tow.

- Contact: Incident as a result of striking an external substance – but not another ship (see collision) or the sea bottom (see stranded) – except where the contact is only momentary and the vessel does not come to a standstill.

- Stranded: Incident as a result of the ship coming to a standstill on the sea bottom, sandbanks or seashore, etc., as well as entanglement on underwater wrecks.

For steps 2 and 3, the details are presented in a later section. The method is derived from a previous study (de Vos, Hekkenberg, & Koelman, 2020), but it is adapted for the more general nature of the present study. Therefore, the IHS SeaWeb® database is used for finding typical ship parameters as well. The dataset containing ship data has been limited to ships built after 1980. Eliopoulou et al. (2016) state that less radical changes in employed shipbuilding technology are observed after 1980, compared to before 1980. As a result, this limitation of the dataset ensures that only 'modern' ships are included in the analysis, thus providing a better estimate of the present-day risk levels.

Steps 4 and 5 respectively provide the annual risk per category of consequence and the overall annual risk associated with navigation-related accidents.

DETERMINATION OF CONSEQUENCES OF ACCIDENTS

The possible consequences of an accident are divided into two main categories: the consequences when the ship survives the accident and the consequences when the ship is lost. Similar to de Vos, Hekkenberg, & Valdez Banda (2020), a summary of the considered categories of the possible consequences of an accident is as follows (Table 1).

Table 1: Summary of accident consequences

Non-ship loss	**Non-ship loss**
Loss of cargo	Loss of cargo
Loss of fuel	Loss of ship
Damaged machinery	Salvage and clean-up
Material damage	Loss of life
Loss of life	

In the following sections, the determination of the cost associated with each category is presented. Furthermore, the probability of occurrence for each category is discussed. Throughout this section, a number of ship parameters are mentioned for the determination of the cost of the consequences. These parameters (such as a ship's deadweight) are different for each ship. However, as mentioned before, the IHS SeaWeb® database is used to find average values for these parameters for each ship type and different length intervals. These parameters are:

- Length
- Lightweight
- Deadweight
- TEU capacity
- Number of holds
- Newbuilding price
- Installed power
- Capacity fuel tanks

Consequences of a non-ship loss

The potential consequences of an accident where the ship is not lost are estimated below for each of the elements mentioned in Table 1.

Loss of cargo

When the ship survives the accident, loss of cargo can still occur if one or more cargo holds are penetrated. The probability of penetrating a cargo hold greatly depends on the circumstances of the accident, such as the impact speed and angle of the ship, and the design of the involved ship. Unfortunately, the casualty data lacks detail on the loss of cargo during accidents. Therefore, an educated guess will be based on the numbers presented by de Vos, Hekkenberg, & Koelman (2020). These numbers show that there is a 10% chance of penetrating a cargo hold during collisions where the watertight integrity is breached (thus the more severe collisions). However, in the present study collisions do not necessarily have to breach watertight integrity.

Furthermore, the present study also considers stranding and contact incidents, which have a generally lower probability of losing cargo. Therefore, it will be assumed that for 5% of all accidents loss of cargo will occur.

The amount of cargo that is lost depends on the number of holds that are penetrated and the amount of cargo in each hold. First, although it is most profitable to always have a fully loaded ship, it is unavoidable that at times not enough cargo is available for a fully-loaded trip. In the worst-case scenario, the ship has to sail to another port empty. Therefore, it will be assumed that on average a ship is 70% loaded at the time of the accident.

Second, usually, a ship is able to survive a damaged cargo hold, even if it has only one since it has to be compliant with damage stability regulations (H. Koelman, personal communication, 15 July 2020). However, as soon as more compartments are penetrated the survivability decreases rapidly. For larger ships, the probability to survive multiple penetrated cargo holds increases. It will be assumed that ships with three cargo holds or less will only be able to survive one damaged cargo hold. For ships with four or more cargo holds it is assumed that the ship is able to survive the penetration of two, or even more, cargo holds. Consequently, it will be conservatively assumed that for these ships on average the cargo in two cargo holds will be lost if loss of cargo occurs during the accident.

Due to a lack of more detailed data, it is conservatively assumed that all cargo in and above a penetrated cargo hold is lost. Especially for containerized cargo, this is an overestimation since the containers above deck do not necessarily have to be damaged if the cargo hold is damaged.

Regarding the cost of losing cargo, different types of cargo lead to different cargo values. E.g. containers are much more valuable than dry bulk. For each ship type, different values for the carried cargo will be used. Next, it is described how the value of the cargo is determined for each ship type and a summary can be found in Table 2.

- For bulk carriers the most important commodities are coal, iron ore and grain, accounting for nearly two-thirds of the maritime dry bulk trade (Chen, 2017). Of these three commodities, grain is the most valuable. Its current value is €185 per tonne, which is higher than the value of coal of €56 per tonne and iron ore of €96 per tonne ("Wheat vs Coal," 2019; "Wheat vs Iron Ore," 2019). The higher value of €185 per tonne belonging to grain will be used as the cargo value for bulk carriers.

- For container ships, an average value of €40,000 per TEU (IHS Markit, 2017) will be used.

- General cargo ships can carry different types of cargo. However, containerised cargo is deemed to be the most expensive cargo. The maximum weight of a TEU is 24 tonnes, which comes down to a minimum cargo value of €1,600 per tonne. Therefore, it will conservatively be assumed that general cargo ships transport containers. The maximum number of TEU a ship can transport will be used as the amount of cargo on board.

- Other cargo ships can carry different types of cargo also. Equivalent to the deduction made for general cargo ships, it will conservatively be assumed that other cargo ships transport containers as well.

- A number of different types of tankers exist, depending on the type of liquid they transport. However, the majority of the tankers are products tankers and large crude oil tankers. As a result, the majority of the liquid that is being transported is crude oil, which will be used for the cargo value of tankers. The current value of crude oil is €36 per barrel ("Crude Oil (petroleum)", 2020), which comes down to €287 per tonne. A more important part of losing cargo for tankers are the clean-up cost of the oil. The cost of the clean-up is estimated at $€37{,}819 * V^{0.7233}$ with V the size of the spilled cargo in tonnes (IMO, 2018).

Table 2: Summary of the determination of the cost of loss of cargo per ship type

Ship type	**Cost loss of cargo**
Bulk carriers	€185 per tonne
Container ships	€40,000 per TEU
General cargo ships	€40,000 per TEU
Other cargo ships	€40,000 per TEU
Tankers	$€37{,}819 * V^{0.7233} + €287 * V$ With V the amount of lost cargo in tonnes

Loss of fuel

For ships that survive the accident, loss of fuel will occur if a fuel tank is penetrated. The loss of fuel constitutes a threat to the environment, similar to the loss of cargo for tankers in section **Fout! Verwijzingsbron niet gevonden.**. The casualty database shows that for navigation-related accidents where the ship survives in 4% of the cases pollution is reported. This number will be adopted, and it is thus assumed that in 4% of the accidents pollution due to the loss of fuel will occur.

The size of the reported spills is unknown, but it is expected to be generally less than the maximum capacity of the fuel tanks. The fuel is most of the time distributed over multiple tanks, which are sometimes located at different sides of the ship. Also, the tanks will only be fully loaded at the beginning of a trip, while the ship can be part of an accident during any stage of the trip. Therefore, it will be assumed that on average the size of the spill is equal to half of the total capacity of the fuel tanks.

The estimation of the cost of loss of fuel is the same as the cost estimation for the loss of cargo of tankers. The value of the spilled fuel will be taken as €285 per tonne. The costs of cleaning up fuel are estimated at $€37{,}819 * V^{0.7233}$ with V the size of the spill in tonnes (IMO, 2018).

Damaged machinery

When a ship survives the accident, but the engine room is penetrated, the machinery in the engine room will be damaged. The analysis in de Vos, Hekkenberg, & Koelman, (2020) shows that for ships that are seriously damaged due to a collision, the probability of a penetrated engine room, while the ship survives the accident, might be somewhere between 4% and 15%. It can be expected that this number will be lower for contact accidents and stranding accidents. For both these accident categories, the impact speed is lower, since only one ship is involved. Furthermore, it can be expected that the ship will hit the obstacle (either above or below water) bow first in most cases, while the engine room is located in the stern of most ships. Because of the absence of exact data on the probability of a damaged engine room, it will be conservatively assumed that for 10% of all accidents machinery will be damaged.

The cost estimation of the damaged machinery is conservatively based on the cost 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 (Aalbers, n.d.). Spills of polluting liquids such as lube oil or black water are not incorporated. The clean-up costs associated with these spills are considered to be low compared to the costs of the drive train because it is expected that only small volumes will be spilled.

Material damage

After an accident that the ship survived, the damage to the ship will have to be repaired before the ship can be used again. Each damage case where the ship remains afloat will have steel damage as a consequence.

In order to perform inspection and repairs, the ship would need to go into a dry dock. Aalbers (Aalbers, n.d.) provides an estimation of the costs of dry-docking of 1-2% of the newbuilding price of the ship, while Hansen (Hansen, 2013) shows that the actual costs of dry-docking are often underestimated. Therefore, conservatively, the costs of dry-docking are estimated as 3% of the new building price.

Next to the costs of dry-docking, the costs of repairs need to be estimated. In de Vos, Hekkenberg, & Koelman, (2020) a method is described to determine the cost of repairing steel damage if the size of the damage is known. The cost estimation in this paper is derived from this method and uses average ship parameters and estimated average damage sizes to find the average cost of repairs per accident.

For each ship type and length interval, the amount of steel per meter of ship length is estimated by dividing the ship's steel weight by the ship length. The actual amount of steel that needs to be replaced depends on the penetration depth of the damage and the length of the damage. Lützen has performed an analysis on damage due to ship-ship collisions (Lützen, 2001). Within the analysis, it is found that ship-ship collisions have more severe consequences than other collisions (considered to be contact accidents). Furthermore, Lützen found that the average penetration depth for collisions is between 8% and 16% of the breadth of the ship. Since ship-ship collisions are considered to cause relatively more damage than contact and stranding accidents, the average penetration depth is expected to be lower for these types of accidents. However, most of the steel structure of the ship is located in the sides and the bottom of the ship. Therefore, it will conservatively be assumed that for all accidents an average of 16% of the cross-section will need to be repaired.

Lützen also found that the damage length increases linearly with the ship length and that the average damage length is roughly 6% of the ship length. This number will also be used as the average damage length per accident in this paper. By using material costs of €850 per tonne of steel (Aalbers, n.d.) and an estimation of 300 required man-hours per tonne of steel (Butler, 2012), the total costs associated with material damage are calculated according to equation **Fout! Verwijzingsbron niet gevonden.** for each ship type and length interval.

$$Cost_{repairs} = €14{,}500 * \left(16\% * \frac{steel\ weight}{ship\ length}\right) * (6\% * ship\ length) + (3\% * newbuilding\ price) \quad [1]$$

Loss of life

The loss of life can be compared to 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 in the probability of loss of life. However, the VPF strongly depends on the GDP of the country the crew is from. As a result, there is a large spread in the VPF per country. According to EMSA, the average VPF is approximately €6.25 million per fatality (European Maritime Safety Agency, 2015b). In order to find the risk associated with loss of life during non-ship losses, the VPF is multiplied by the average number of lives lost per year during accidents the ship survives.

Besides the 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, 2015b). Each of these methods combines the non-fatal injury risks with the risk of losing a life. The current maritime approach takes serious injuries into account with a fraction of 0.1 in the total number of fatalities (10 serious injuries is equal to 1 fatality). Minor injuries are accounted for with a fraction of 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.

Based on general numbers presented by EMSA an estimation can be made on the contribution of injuries, and, therefore, the possible error in the calculation of the risk associated with life at sea. In an annual overview, EMSA reports that in between 2011 and 2018 roughly 150 lives have been lost during navigation-related accidents. In the same period around 615 people have been injured during navigation-related accidents. Assuming the worst-case scenario, where all injuries are serious injuries, and using the method as described above, the number of lives lost should be multiplied by a factor of 1.4 to account for injuries. However, it is unlikely that all injuries are serious injuries, thus a factor of 1.4 is a maximum. Furthermore, it is unknown if this derivation holds if only cargo ships are considered and how the number of injuries is distributed over ship length. Therefore, injuries will not be accounted for in the risk analysis as presented in this paper.

Consequences of a ship loss

The potential consequences of an accident where the ship is lost are estimated below for each of the elements mentioned in Table 1.

Loss of cargo

The value of the cargo onboard the ship will be lost if the ship is lost. The determination of the cost associated with the loss of cargo when the ship is lost is almost identical to the calculations in the section for non-ship loss. The only difference is that in this case all cargo is lost. Again, it is assumed that all ships are on average for 70% loaded at the time of the accident.

Loss of ship

When a ship loss occurs, the value of the ship is lost as well. It is assumed that ships are depreciated linearly over their entire lifetime towards their scrap value and that on average ships are lost halfway through their expected lifetime. A part of the ships in the IHS SeaWeb® database has already been scrapped. The average lightweight recycling price for these ships is €389 per tonne.

Salvage & clean-up

Ships that have been lost might need to be removed. The salvage and clean-up activities are highly dependent on the circumstances of the accident. Because of the different circumstances of accidents, it is not always necessary, or even possible, to remove a ship. Using the numbers from both the International Salvage Union (ISU) and the IHS SeaWeb® database, it can be determined for how many accidents it can be expected that wreck removal is needed. In between 2014 and 2018, 477 wreck removal services have been provided (ISU, 2016, 2017, 2018, 2020). In that same period, 883 ships have been lost (including all ship types). This means that for a little more than half of the ship losses, wreck removal services are provided. Therefore, it will be assumed that for 50% of the accidents resulting in a ship loss salvage and clean-up costs are applicable.

EMSA provides an estimate of the associated cost for these activities of one to three times the newbuilding price of the ship (European Maritime Safety Agency, 2015a). Furthermore, the annual overviews from the ISU show that the turnover associated with the removal of wrecks of all ship types and all causes is on average €287 million per year (ISU, 2016, 2017, 2018, 2020).

As a result, one time the new building price will be taken as cost for salvage and clean-up. The risk analysis will show that this results in a yearly cost of salvage and clean-up that is a little lower than the annual turnover from the ISU. This can be expected since the turnover from the ISU includes all ship types and all accident types.
The cost of salvage and clean-up will include both removing the wreck and the clean-up of any potentially hazardous material, such as fuel and cargo. Only for tankers, the clean-up of the cargo is included in the cost associated with the loss of cargo.

Loss of life
The risk associated with loss of life during ship losses is found analogous to loss of life during non-ship losses, as presented in section 0. In this case, the VPF will be multiplied by the average number of lives lost per year during accidents the ship is unable to survive.

RESULTS AND DISCUSSION

In this section, the annual risk associated with navigation-related accidents is discussed. In the first sub-section, the figures of the casualty analysis are presented, which will be used together with the numbers from the previous section to perform the risk analysis. In the next sub-section, the results of the risk analysis are presented as the annual risk associated with navigation-related accidents. The results of the risk analysis come with significant uncertainties because of assumptions made in the previous section. These uncertainties will be discussed in the final sub-section.

Casualty analysis
In this section, the results of the casualty analysis of navigation-related accidents with cargo ships between 2000 and 2018 are presented. To be able to reflect the casualty analysis on the number of ships that sail around, the composition of the world fleet per ship type and ship size is presented in Figure 1. The fleet is represented by the average number of ships per year, calculated over the period between 2000 and 2018.

The numbers from the casualty analysis are presented as numbers per year since we are estimating the risk per year. First of all, in this period 7329 navigation-related accidents were reported, which comes down to an average of 386 per year. In Figure 2 an overview can be found of the average number of navigation-related accidents per year, divided by ship length and ship type.

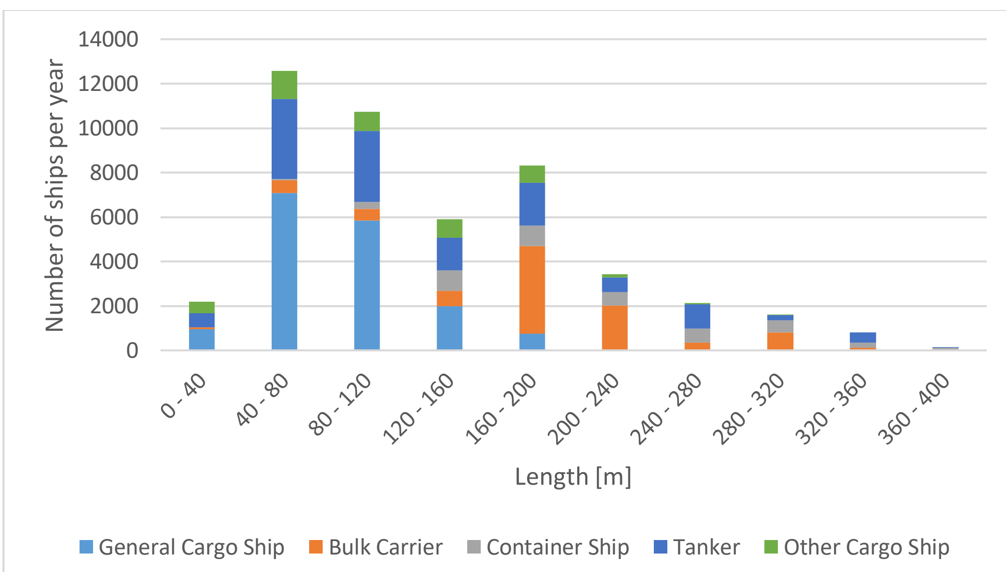

Figure 1: The average number of ships in the world fleet per year.

The distribution in Figure 2 can for a large part be explained by the distribution of the world fleet, as presented in Figure 1. Figure 2 shows that the number of accidents decreases for larger ships, which is at least partly explained by the fact that the larger ships are fewer in number. The length interval 160 to 200 meters spikes out of the slope, because of the high number of so-called handymax ships. This also explains the high contribution of bulk carriers to this length interval, since handymax ships are mostly bulk carriers that are able to access most smaller ports. Most of the smaller ships are general cargo ships, and as a result, most accidents in that size group are associated with general cargo ships. However, the number of reported accidents for the length interval 40 to 80 meters stands out. The number of ships of this length is similar to the number of ships between 80 and 120 meters. However, the reported number of accidents for ships between 40 and 80 meters is almost half, which suggests serious underreporting for ships within this interval.

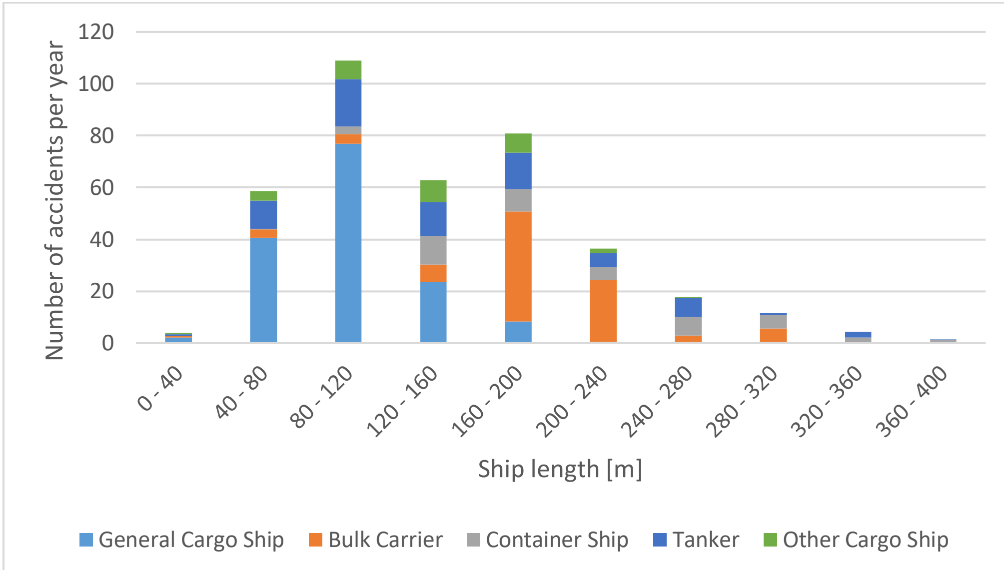

Figure 2: The average number of navigation-related accidents per year, based on reported accidents between 2000 and 2018.

Accidents with these smaller ships of under 200 meters are also the most severe accidents. In total, 667 of the reported navigation-related accidents between 2000 and 2018 resulted in a ship loss, which comes down to 35 ship losses per year. The distribution of ship losses over ship length and type can be found in Figure 3. As can be seen, most of the ship losses are associated with ships of under 200 meters. Furthermore, since most accidents with smaller ships are associated with general cargo ships, most of the ships that have been lost are also general cargo ships.

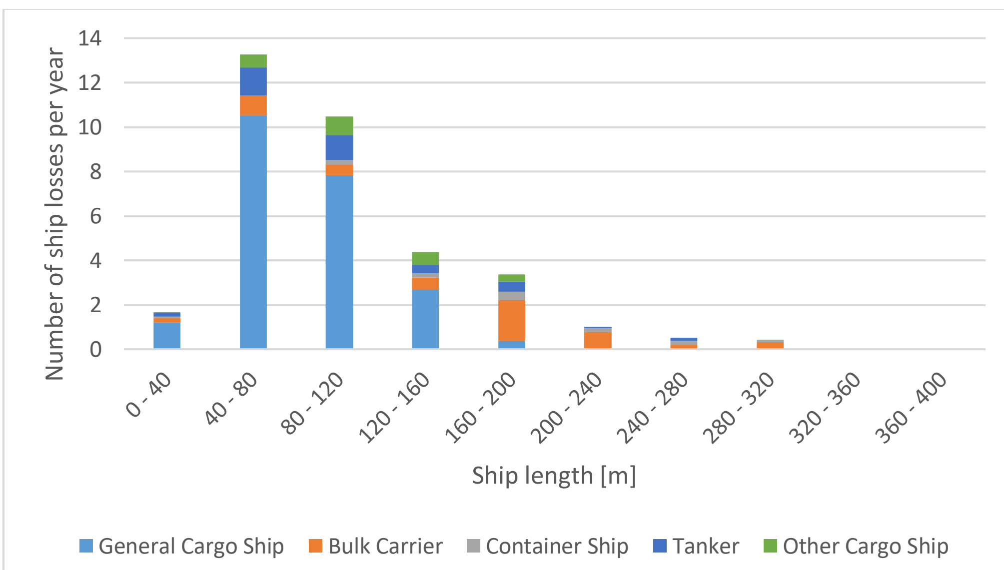

Figure 3: The average number of ships that are lost due to navigation-related accidents per year, based on accident statistics from 2000 to 2018.

In Figure 4 the distribution of lives lost over ship length and ship type can be found. Over the period 2000 to 2018, a total of 793 lives have been lost during navigation-related accidents with cargo ships, which comes down to 42 per year. In Figure 4 no distinction has been made between lives lost when the ship survives the accident or is lost during the accident. However, as was also found in de Vos & Hekkenberg, (2020), almost 90% of the lives are lost when the accident leads to a ship loss. Therefore, the distribution in Figure 4 can largely be explained by the distribution of Figure 3. Figure 3 showed that most severe accidents occur with small general cargo ships. As a result, most lives lost are associated with small general cargo ships as well.

The peak in the number of lives lost for the interval 240 to 280 meters can be attributed to the loss of the tanker Sanchi, which resulted in the death of all 32 crew members. Such a severe navigation-related accident with cargo ships only occurs once every 15 to 20 years.

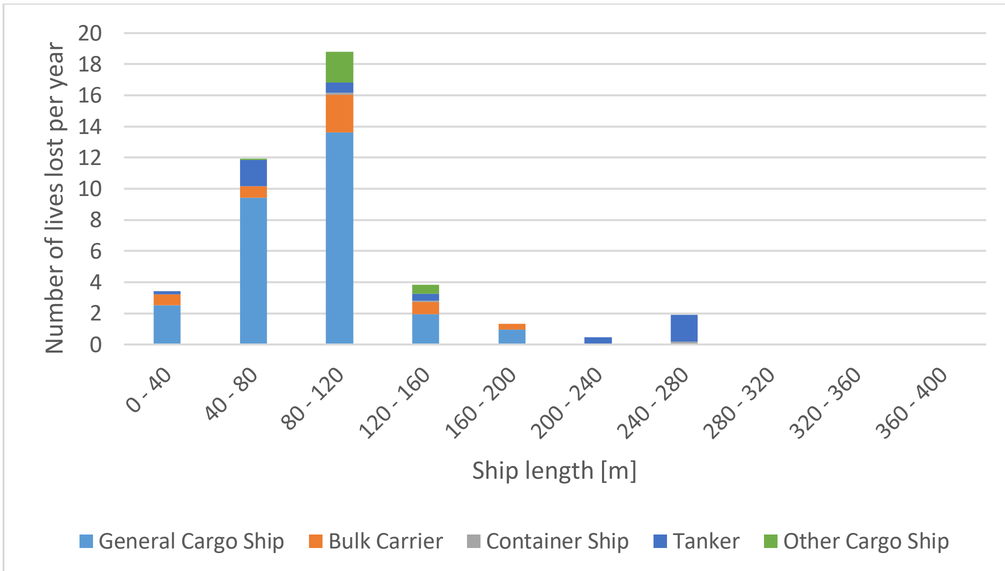

Figure 4: The average number of lives that are lost during navigation-related accidents per year, based on accidents statistics from 2000 to 2018.

Results of the risk analysis

As mentioned, the risk per year is found by multiplying the cost of the consequences with the probability of occurrence per accident and the average number of occurrences per year. In this section, the results are presented. Again, the numbers presented in this section are ballpark figures and the accompanying uncertainties are described in the final section.

On average, the risk associated with navigation-related accidents is roughly €2.03 billion per year. In Figure 5 the distribution of the total risk per year over the various ship length categories can be found. In Figure 6 the contribution in percentages of each category of consequence to the risk for each length interval is presented.

From Figure 5 it can be seen that the contribution of each length interval largely corresponds to the number of accidents that are associated with each length interval (see also Figure 2). The decrease in contribution when the ships become larger is smaller compared to the number of accidents since the cost per accident associated with larger ships is higher. As a result, the length interval 160 to 200 meters is the largest contributor to the risk per year. Although this is not the length interval with the most reported accidents, the increased value of ship and cargo results in a higher total risk than for the smaller ship intervals at which most accidents occur.

The single most important driver for the overall risk per year is 'non-ship loss: material damage' (31%). It is followed by the categories belonging to 'ship loss': 'loss of cargo' (17%), 'loss of life' (11%), 'salvage & clean-up' (11%) and 'loss of ship' (10%). However, the contribution of each category of consequences changes over ship size, as can be seen in Figure 6. For ships under 160 meters, half or more of the risk per year comes from ships that have been lost. For the smallest ships, an important part of the risk of a ship loss comes from the loss of life. As can be expected from Figure 4, the contribution of loss of life rapidly decreases when the ships become larger. Also, since almost 90% of the lives lost are associated with a ship loss, the contribution of loss of life to the risk associated with non-ship losses is very low.

Furthermore, Figure 6 shows the importance of considering non-ship loss accidents when evaluating safety at sea. For all ships over 120 meters, the risk associated with non-ship loss accidents covers an unignorable part of the risk per year. Only for smaller ships, under 120 meters, the cost associated with ship losses and loss of life seriously outweigh the cost of non-ship loss accidents. As a result, only for these smaller ships, the risk associated with navigation-related accidents can be represented by ship losses and loss of life.

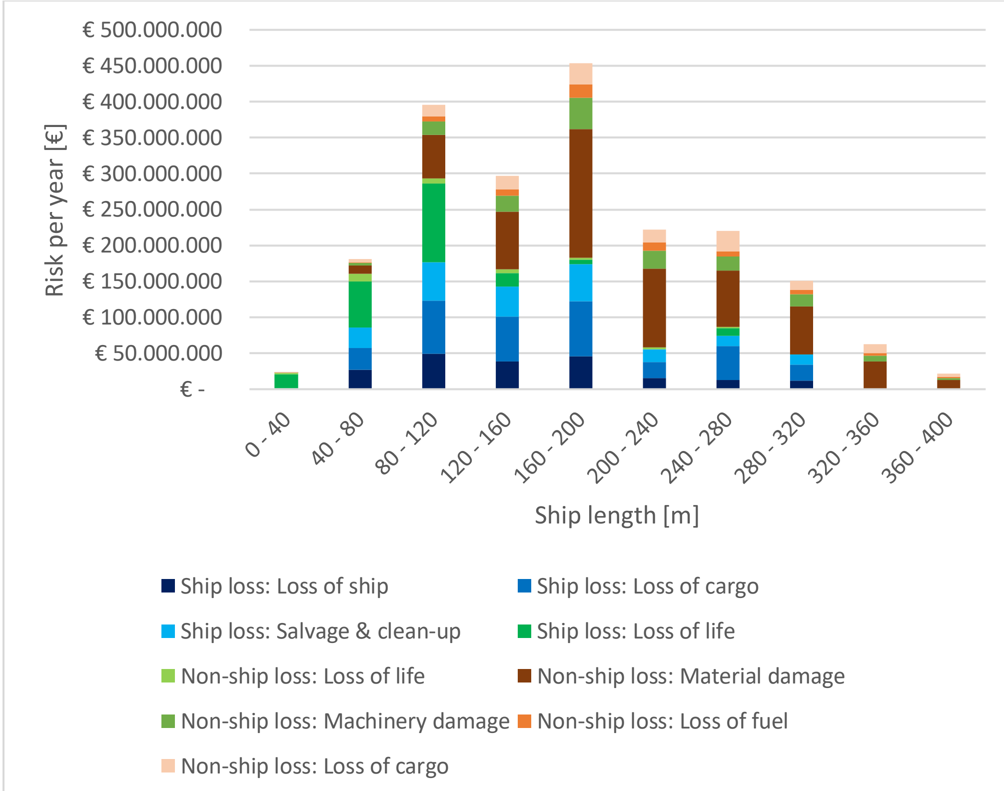

Figure 5: Average risk per year, associated with navigation-related accidents.

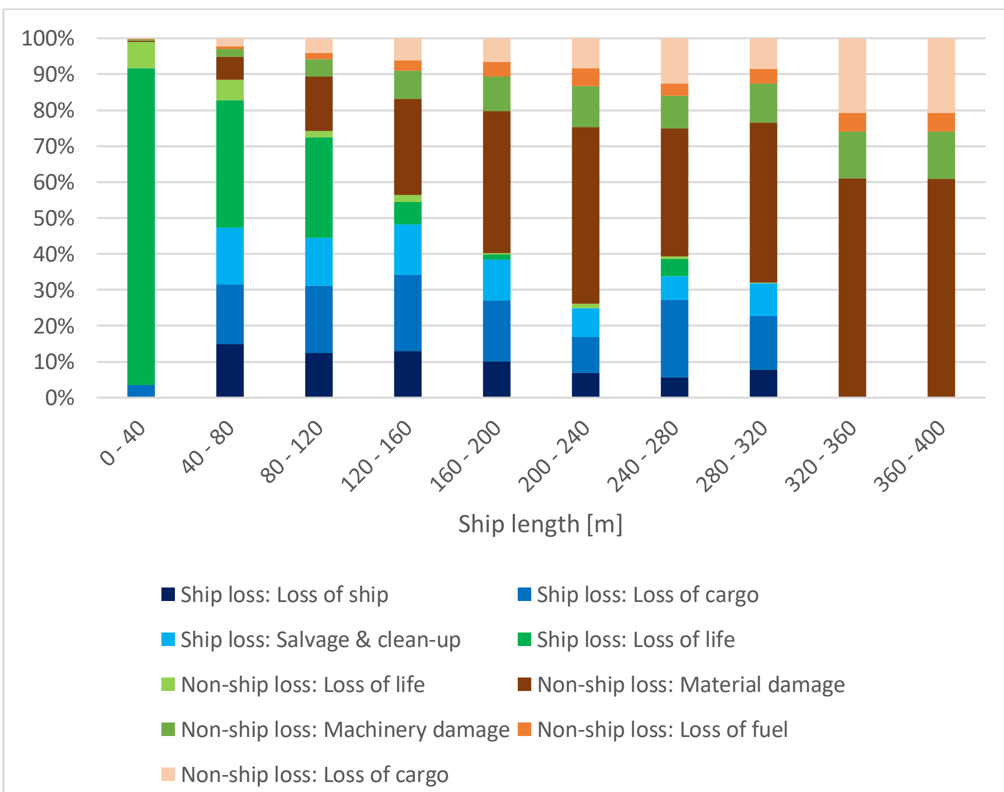

Figure 6: Contribution in percentages of each category of consequence to the average risk per year, associated with navigation-related accidents.

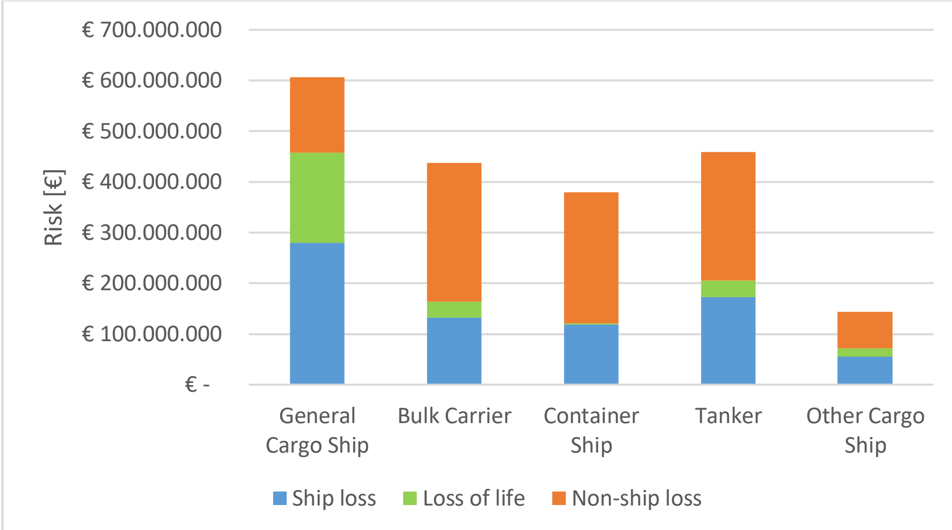

Figure 7: The average risk per year associated with navigation-related accidents per ship type.

In Figure 7 the average risk per year associated with navigation-related accidents is presented per ship type. In this figure, the subdivision of the risk has been limited to the overarching categories, namely 'ship loss', 'loss of life' and 'non-ship loss'. In this figure 'loss of life' is presented as a separate category in order to be able to see its contribution to each ship type. As can be seen, the largest contributors to the overall risk per year are general cargo ships. This is mainly due to the high number of ship losses and loss of life associated with this category, as is apparent from Figure 3 and Figure 4.

Furthermore, bulk carriers, container ships and tankers all contribute to the overall risk per year with similar numbers. However, this is remarkable for container ships, since these account for a significantly lower part of the world fleet and the number of accidents compared to bulk carriers and tankers. Container ships are generally larger ships and the cargo of containerships has been determined as relatively valuable compared to bulk carriers and tankers. As a result, the cost of the consequences is higher for container ships, which results in a relatively high risk per year.

Average risk per vessel

The final step in this process is calculating the average navigation-related accident risk per vessel per year. These values will allow a designer to contemplate the lifetime savings of the vessel connected to the autonomous navigation system. As can be seen in Figure 8, these costs do vary per shiptype and length interval. In some cases the low number of ships and the presence of a single accident can lead to extreme values, in case of the tankers in the largest size range two ships were identified and 1 accident occurred in the 18 years investigated, leading to a relatively high chance and thus a high risk.

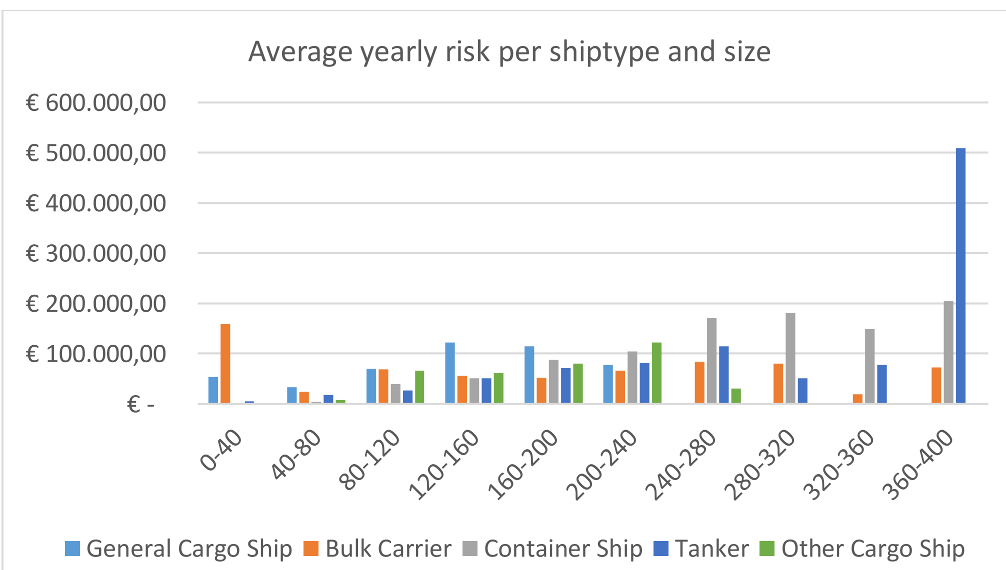

Figure 8: The average risk per ship per year associated with navigation-related accidents

For the smallest size interval, it is interesting to note that the single containership in that interval had 3 accidants, but none with major concequences, however the 27 bulk carriers had 5 accidents including for ship losses and a total of 13 fatalities. This explains the high risk seen here. On average these risk costs amount to €62k per year per vessel and the risk costs increase with size. Up to 80 meters they are below €50k, while between 80 and 240 meters they are between €50k and €100k. Finally, above 240 meters the average is between €100k and €200k. Assuming the costs of an autonomous navigation system has only a limited dependence on length and a high initial costs for the system, larger vessels offer a higher potential of its installation based on the risks of navigation related accidents.

Uncertainties in cost determination

Earlier, the determination of the cost of consequences and the associated probability of occurrence has been described. Due to the high-level nature of the analysis, assumptions had to be made for each category. Some of the major uncertainties accompanying these assumptions will be discussed in this section, alongside the effects on the result of the risk analysis. In Table a summary of the effects of the uncertainties is given.

First of all, the issue of valuing a human life remains a very delicate subject. Expressing human lives in monetary values is a useful method, but a serious topic for discussion in terms of determining the height of the VPF. Furthermore, non-fatal injuries are still excluded from the estimated risk associated with loss of life. Consequently, the risk that the ship's crew is exposed to can be expected to be higher than presented. In section 0 it has been mentioned that in the worst-case scenario the number of fatalities should be multiplied by 1.4 in order to account for all injuries. If this factor would be applied, the total risk associated with navigation-related accidents increases to €2.13 billion per year.

When inspecting the largest contributor to the overall risk, 'non-ship loss: material damage', the dominating uncertainty is the size of the damage. The average damage size has been generalised for all ship types and sizes and all three accident types. The damage size has mainly been based on statistics concerning collisions, which are believed to be the most severe of three considered accident types. Therefore, the effect of a smaller damage size on the overall risk will be evaluated. To do so, the average damage length is decreased from 6% to 3%, effectively cutting the repair costs in half. The result of this change is that the total risk associated with navigation-related accidents is decreased to €1.84 billion per year.

A third important uncertainty is the average amount of cargo carried at the time of the accident. Above, an average loading condition of 70% has been taken. However, a simpler approach is to assume that each ship sails fully loaded to its destination and that it will sail back with empty holds. This would result in an average loading condition of 50%, which is a significant decrease from the original assumption. However, this will only lead to a decrease in the total risk associated with navigation-related accidents to €1.90 billion.

The three uncertainties as described above are three of the major uncertainties associated with the assumptions made in the methodology section. In Table the effect of these uncertainties on the result has been summarized. Although the proposed changes are of significant size, it can be seen that the effect on the result is limited to €0.10 – €0.20 billion. Consequently, it can be assumed in all likelihood that the estimated €2.03 billion is in the ballpark.

Nevertheless, it can very well be that the presented method leads to an overestimation or underestimation of some of the categories. However, since it is found that the effect of one uncertainty is limited to €0.10 – €0.20 billion, it is believed that the actual risk associated with navigation-related accidents can be expected to be between €1.50 billion and €2.5 billion.

Table 3: The effect of the major uncertainties in the determination of the cost of the consequences.

Change in the risk analysis	Overall risk per year [billions]	Percentage change
Original	€2.03	-
Number of lives lost multiplied by 1.4	€2.13	+5%
Average damage length decreased to 3%	€1.84	-9%
Average amount of carried cargo decreased to 50%	€1.90	-6%

CONCLUSIONS

As mentioned, in earlier work (de Vos, Hekkenberg, & Valdez Banda, 2020) the risk associated with navigation-related accidents had been represented by the number of lost ships and lives. Such a value is of little insight to designers and therefore in this paper, it was the intention to provide a more complete risk analysis of navigation-related accidents with cargo ships and to roughly estimate the annual risk. Allowing a designer to make an informed estimation of the benefits of an autonomous navigation system.

The risk analysis shows that the risk per year is roughly €2.03 billion. However, due to uncertainties and assumptions in the determination of the consequences of an accident, the actual value can be expected to be between €1.50 billion and €2.50 billion per year. This translates to an average of €60k per vessel per year with a variation between €45k and €75k

Furthermore, it has been found that for ships below 120 meters, the risk associated with ship losses is dominant to such an extent, that the remaining risk associated with non-ship losses might be negligible. The distribution between the risk associated with ship losses and non-ship losses changes when the ship's size increases, such that for the largest ships the risk associated with ship losses can be neglected.

In terms of ship size, the largest contributors to the total risk are ships between 160 and 200 meters. Although this is not the interval with the largest number of accidents, ship losses and lost lives, the associated risk is highest due to the increasing value of ship and cargo if ships become larger. The largest number of accidents, ship losses and lost lives are associated with smaller ships, which are mainly general cargo ships. As a result, general cargo ships are the largest contributors to the total risk in terms of ship type.

Finally, overall the risks per ship per year increases with the size of the ship. Although variation can be found from one size category to the next, this is more likely to be attributed to the limited dataset than underlying features of the vessel.

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