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# The Impact of Autonomous Ships on Safety at Sea – A Statistical Analysis

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ABSTRACT

The advent of autonomous ships that are unmanned or low-manned will reduce the number of people at risk at sea. Even when autonomous navigation does not reduce the number of accidents, this means that safety at sea will increase. In fact, increased safety is one of the primary perceived drivers for autonomous shipping, although this safety increase has not yet been quantified in academic literature. In this article a statistical analysis is performed to determine the distribution of human casualties and lost ships over accident types, ship types and ship sizes. Subsequently, based on several scenarios for the implementation of autonomous ships, a quantification of the estimated reduction in loss of life and loss of ships is provided. It is concluded that the implementation of autonomy on small cargo ships with a length below 120 m will have the largest safety benefit, since these ships account for the majority recorded ship losses and lives lost.

## 1. Introduction

The research effort in the field of autonomous ships has increased significantly in the last decade. Several projects have been launched to explore the feasibility of autonomous ships. Among these projects are the MUNIN project [1], the AAWA project [2], the YARA Birkeland demonstrator [3], the REVOLT concept [4] and the project Design For Value (D4V) [5].

Various projects use different definitions of autonomous ships. In this article, when we speak of autonomous ships, we refer to fully autonomous ships as defined in the IMO's regulatory scoping exercise on maritime autonomous surface ships (MASS): i.e. ships whose operating system is able to make decisions and determine actions by itself. The advent of such autonomous ships will logically lead to a reduction of crew sizes or even to completely unmanned ships. Several benefits can be named for sailing with a reduced number of crew members. It is expected that in the coming years a shortage in manning will occur. It has been predicted that by 2025 an additional 147,500 officers are needed [6]. The possibility to sail with a reduced crew can counteract this predicted shortage. A second benefit is perceived economic efficiency [7,8]. Especially for smaller ships, the crew wages are an important part of the ship's expenses. Furthermore, unmanned ships no longer need accommodation and the associated ship systems. This simplifies the design, increases cargo carrying capacity and lowers building costs [9,10]. Together, these aspects can lead to a significant cost reduction. As long as the additional costs of making the ship autonomous do not outweigh this cost reduction, this improves the ship operator's competitive position. In addition De Vos et al. [11] propose that design regulations that are intended to safeguard the lives of the crew can be reconsidered to further improve the economic efficiency of the design. However, overall, only a limited amount of research has been conducted in this area.

A third perceived benefit is that autonomous ships will make shipping safer. It is a widely adopted view that a significant part of all accidents at sea involve a human erroneous action. Numbers range from approximately 60% to 90% [12–18]. However, there are only a few sources that base their statement on own research [17,18]. Coraddu et al. [12] and Navas de Maya et al. [14] refer to Rothblum [13], but Rothblum subsequently refers to studies performed in the early nineties. More recently, Wróbel et al. [18] conclude that their analysis suggests that at least 60% of the accidents have been caused by human errors. An overview of EMSA shows that for 65% of the recorded accidents the main contributing cause is a human erroneous action [17].

As a result of the contribution of human errors on the safety at sea, numerous studies address this subject for autonomous ships. Examples are Wróbel et al. [19], who propose a model for safety assessment of autonomous merchant ships, Fan et al. [20], who identify factors influencing navigational risk for autonomous ships and Utne et al. [21], who outline a framework for risk modeling for autonomous ships. Additionally, multiple studies [22–25] address the human-system

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interaction for autonomous ships. Furthermore, due to the high impact of human errors, it is expected that the number of accidents will be reduced when autonomous ships are introduced [18]. However, thus far it has not been quantified what percentage of accidents can be prevented by autonomous ships.

The difficulty of estimating the reduction can partly be attributed to the fact that often an accident is not the result of a pure human error. Failing systems occur and it is left to the crew to solve these failures. The system failures that the crew is able to solve, are usually not reported. However, the system failures that the crew is not able to solve, can be reported as a human error, because the human did not respond adequately to the system failure [26]. It is thus unclear which part of the reported human errors can indeed be solved by an autonomous systems, especially since the reliability of such systems in day-to-day operations still needs to be demonstrated.

Despite the above, this article intends to shed light on the increase of safety that is to be expected from autonomous ships. The bandwidth of the expected decrease in accidents when autonomous ships are introduced is explored and the impact of autonomous ships sailing with a reduced number of crew members or without any crew on overall safety is investigated.

In order to estimate the extent to which safety at sea, expressed in loss of lives and loss of ships, will increase and which ship types and sizes will benefit most, a casualty analysis is executed.

The distribution of human casualties and ship losses over incident types, ship types and ship sizes is provided and, subsequently, based on several scenarios for the implementation of autonomous ships, a quantification of the estimated reduction in loss of life and loss of ships is provided.

First, in section 2 the method of this paper is described. In section 3 the results of a statistical casualty analysis are presented. In section 4 these results are used to evaluate the scenarios that are described in section 2.4. In section 5 the results of the evaluation are discussed and summarized.

## 2. Method

This section will first discuss our overall approach. This is followed by the expected impact of autonomous ship technology on the number of accidents and the associated consequences, which provides focus for the following analyses. Thereafter, a description of the executed casualty analysis is provided. The section concludes with a detailed presentation of the various autonomous shipping scenarios that will be investigated.

### *2.1. Overall approach*

To assess how safety at sea is affected by autonomous ships, we use two metrics: the number of lives lost during shipping accidents and the number of ships that are lost. Both metrics are imperfect but we believe them to provide a reasonable approximation of actual safety levels at sea as far as cargo ships are concerned. By using loss of life in shipping accidents as a proxy for safety of life, the impacts of non-lethal injuries and casualties of workplace accidents are disregarded, but due to a lack of sufficiently reliable and detailed data about this, this is unavoidable. The use of the number of ships that are lost is imperfect because A) not all ships are identical and carry the same type and amount of cargo, so the monetary consequences of losing one ship are different from those of losing another, and B) the risk contribution of ships that are involved in an incident but are not lost is disregarded. By subdividing ships by type and size, the uncertainty that stems from issue A is reduced as much as possible, given the fact that insufficient data is available to accurately quantify the monetary consequences of the loss of large numbers of individual ships. Regarding issue B, previous research by De Vos et al. [11] has shown for a number of different cases that the loss of a cargo ship, including the loss of its cargo, leads to vastly larger monetary consequences than incidents where the ship remains afloat. When a ship remains afloat, this nearly always implies that not all cargo holds are penetrated and, as a consequence, not all cargo should be considered lost. Furthermore, especially in case of navigation-related accidents, the ship will not be damaged beyond repair. This justifies the focus on ships that are lost. It does, however, not imply that the cost associated with accidents where ships remain afloat is small by definition. E.g. in case of an incident that leads to extreme roll motion, high-value cargo like containers or cars can be damaged, even when the damage to the ship itself is limited. There is, however, insufficient detail available in the accident statistics to account for such cases.

To determine which types of shipping accidents lead to which loss of life and loss of ships, the IHS SeaWeb® database is used. Accidents taken from this database are categorized by accident type, involved ship types and involved ship sizes and for each category the number of lives and ships lost is determined. This provides an overview of current safety levels and provides a basis for a number of scenarios where autonomous operation or removal of the crew are applied to 1) only small cargo ships, 2) all cargo ships and 3) all ships mentioned in section 2.3.1. For each of these scenarios it is determined how many fewer lives and ships are lost, thus providing a proxy for the increase in safety.

### *2.2. Estimating the effect of autonomous ships on accident probabilities*

As mentioned earlier, it is expected that the number of accidents will go down if autonomous ships are introduced. However, the consequences of introducing autonomous ships will be hard to predict accurately. The risk of human errors will be potentially transferred to a new and distinct part of the system responsible for the safety assurance of the ship [7]. The accident statistics do not show how many accidents have been prevented due to human action and the reliability and quality of autonomous navigation system has not yet been proven in day-to-day practice.

Nevertheless, it can be expected that the number of accidents will not become larger if autonomous ships will be introduced, since this would lead to major acceptance issues given the fact that an important criterion for autonomous ships is that they should be at least as safe as the most advanced manned ships [27,28]. This represents an initial high-level demand that requires innovative approaches to develop safety assurance strategies to ensure this target is met [29]. To overcome this lack of reliable estimates, in this article we refrain from predicting the change in the number of accidents, but will discuss the safety effects as a function of the percentage of accidents that are prevented. The majority of research related to autonomous ships anticipates safety benefits from autonomous navigation, while the maintenance and operation of the ship and its machinery are perceived as major challenges rather than as anticipated safety-improvement aspects. In this analysis we, therefore, only assume positive changes in the number of navigation-related incidents while incidents related to fire/explosion, hull/machinery damage, foundering and hostilities, i.e. the non-navigation-related accident categories from the database, are considered unaffected.

### *2.3. Casualty data*

The IHS SeaWeb® database is used for the analysis of casualty data. Multiple databases exist for the collection of accident data, but the quality of the data can be questionable, depending on the source [30]. The European Maritime Safety Agency has a publicly available database called EMCIP (for access, permission by the member states may be needed). However, this database only contains data from European flag states, and it depends on the states' policy which accidents are documented in EMCIP. IMO has a similar database called GISIS, but the publicly available data is not complete or ready to use for analysis. The IHS SeaWeb® database is a commercial database. The data in it is actively monitored and updated and it covers accidents from all over the world.

The casualty data used in this article consists of all recorded serious shipping accidents concerning cargo ships from 2000 to 2018. Serious shipping accidents are defined by IHS Markit as those accidents where the ship incurred significant damage and/or was withdrawn from service. Although the definition of serious events is ship-centered, 99% of all lives lost during shipping accidents are allocated to serious shipping accidents, justifying the choice to only include these accidents. Besides lives being lost during shipping accidents, lives can also be lost due to workplace incidents (e.g. slipping or falling overboard). In an overview from 2011 to 2018, the European Maritime Safety Agency (EMSA) classified these accidents as "fatalities by deviation" [17]. In this period, EMSA recorded 696 fatalities of which 388 are fatalities by shipping accidents and 308 are fatalities by deviation. As a result, it can be expected that the fatalities in the IHS SeaWeb® database only account for roughly 55% of all fatalities, since the fatalities by deviation are excluded. However, the data of fatalities by deviation is not available in the same extent and detail as the casualty data, since EMSA only provides a rough overview and contains only European flag states. Furthermore, EMSA does not specify where and when the fatalities by deviation occurred (i.e. in port, during berthing or (un)loading or in transit). Therefore, an analysis of when and where lives are lost by deviation and whether these lives can be saved by creating autonomous and/or unmanned ships has not been performed. Consequently, the safety benefit of removing the crew from autonomous ships as presented in this article can be expected to be higher, since the fatalities by deviation have not been taken into account. The safety benefit of a reduced number of navigation-related incidents is not affected.

#### 2.3.1. Ships included in the analysis

The dataset that is used has not been limited by ship size, but ships built before 1980 are excluded. This limitation is adopted from the statistical analysis performed by Eliopoulou et al. [31]. It is the intention to use ships in the analysis that are built with similar shipbuilding technology. According to Eliopoulou et al. [31] less radical changes in employed shipbuilding technology are observed after 1980, compared to before 1980. Although it would be best to compare future ships with technology that is used in present shipbuilding only, further limiting the number of recorded accidents will increase the uncertainty of the statistical analysis. Furthermore, the current dataset allows us to use a large set of data points to learn from previous experiences in order to develop a sufficiently robust analysis.

The analysed dataset is divided into categories, using the StatCode 5 ship type coding system as is used by IHS Markit. Not all ship types are included in the analysis and only cargo carrying ships, fishing ships and service ships are included. Passenger ships are excluded because they are specifically built to carry people. This makes an analysis of the reduction of loss of life due to the removal of all people from the ship irrelevant. Furthermore, the selection excludes the categories non-merchant, inland waterways, non-propelled and non-ship structures as well. The resulting dataset consists of the following categories and covers 90% of the world fleet:

- General cargo/multipurpose ships (defined in the database as 'general cargo ship')
- Bulk carriers
- Container ships
- Tankers
- Other cargo ships (e.g. Ro-Ro cargo, refrigerated cargo, livestock, etc.)
- Fishing
- Offshore
- Miscellaneous (e.g. towing/pushing, research, dredging, etc.)

#### 2.3.2. Categorization by type and size

De Vos et al. [11] have observed differences in the probability of losing life depending on the type of ship that is involved in an accident, considering general cargo/multipurpose ships, bulk carriers and container ships. It is expected that these differences can be explained by the difference in average size per ship type: e.g. if a large ship and a small ship collide, there are likely to be more casualties on the small ship since it will sustain more severe damage. Therefore, the differences per ship type and size will be evaluated in the casualty analysis as well.

In the work of De Vos et al. [11] it has already been speculated that the probability of losing lives is larger for smaller ships. However, at the time this speculation was not validated due to a lack of available casualty data. A second reason to differentiate by ship size is that the probability that ships will become fully autonomous strongly depends on their size, as will be discussed in section 2.4.

#### 2.3.3. Categorization by accident type

The casualties in the IHS SeaWeb® database are subdivided in eight categories. The definitions of these categories of shipping accidents as provided by IHS Markit are as follows:

- Collisions: Incident as a result of striking or being struck by another ship, regardless of whether under way, anchored or moored. This category includes collision with drilling rigs/platforms, regardless of whether in 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 ship does not come to a standstill.
- Fire/Explosion: Incident as a result of fire and/or explosion where it is the first event reported. It, therefore, follows that casualties including fires and/or explosions after collision, stranding etc., would be categorised under 'collision' or 'stranded' etc.
- Foundered: Ships which sank as a result of heavy weather, springing of leaks, breaking in two etc., but not as a consequence of any of the other categories listed.
- Hull/Machinery Damage: Hull/machinery damage or failure which is not attributable to any other category.
- Missing: After a reasonable period of time, no news having been received of a ship and its fate being therefore undetermined.
- 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.
- War-loss/Hostilities: Incidents causing loss of or damage to a ship as a result of a hostile act.

Most of the categories have a clear distinction between them. However, the line between hull/machinery damage and the other categories is not always clear. The starting point for categorizing an accident as hull/machinery damage is that hull or machinery failure needs to be the first reported event. However, most of the severe 'hull/machinery damage' accidents are accidents where the ship took water and subsequently foundered. The cause of the ship taking water is not always described in detail and 'took water' or 'developed list' are often given as initial event, while the accident is classified as 'hull/machinery damage'. Furthermore, accidents are reported according to their initial event, which ensures that there will not be duplicates in the dataset. War-loss/hostilities are different from the other types of incidents since the deliberate nature of these incidents formally classifies them as security risks rather than safety risks. They are, however included in the analysis to provide a complete picture of the risk that seafarers and ships are exposed to at sea.

### 2.4. Autonomous shipping scenarios

In order to assess the impact of autonomous shipping on the safety at sea, six scenarios will be discussed. A summary of these scenarios, and the order in which they will be discussed in section 4, is presented in Table 1.

The first distinction in the scenarios is the influence of autonomy on

**Table 1**
The six scenarios which will be used in this article. Each scenario is given a number for reference. The numbers are given in the order in which they will be addressed in section 4.

| | All cargo ships <120 m autonomous | All cargo ships autonomous | All ships autonomous |
|---|---|---|---|
| Ship becomes completely unmanned, but autonomy has no influence on number of accidents | 1 | 2 | 3 |
| Autonomy decreases number of navigation-related accidents by X%, but no significant reduction in crewing level | 4 | 5 | 6 |

the number of accidents and crewing level. As mentioned in section 2.2, it is difficult to predict if autonomy will decrease the number of shipping accidents. However, reducing crewing levels will naturally reduce the number of lives lost in shipping accidents and, thus, increase safety at sea. Scenarios 1, 2 and 3 will focus on this effect. These scenarios assume that autonomous ships will become completely unmanned, but that the number of shipping accidents will be similar to that of conventional ships.

However, it can be expected that automating the navigation on board ships will only have a limited effect on crewing levels [32]. As a result, the navigation safety of autonomous ships might increase, but the number of crewmembers on board will remain nearly the same. Scenarios 4, 5 and 6 will, therefore, assume that autonomous systems decrease the number of navigation-related accidents (i.e. collisions, contact and stranding), but that there will be no significant decrease in crewing levels. However, as mentioned in section 1, it is still uncertain what percentage of the navigation-related accidents can be prevented by automation. Therefore, in this article we will evaluate the entire range between 0% and 100% reduction in navigation-related accidents.

Furthermore, the scenarios differ by the ship types that will become autonomous. The first variant is that only the small cargo ships under 120 m (roughly half of the world fleet of cargo ships) will become fully autonomous and unmanned. This is plausible based on the fact that for these small ships, the crew represents a much larger share of the total cost than for large ships and that due to their smaller systems, replacing conventional systems by autonomous ones will be less expensive. The second variant is that all cargo ships will become unmanned. The third, most extreme variant is that all ships under consideration in this article will become unmanned, despite the fact that the tasks performed on service ships and fishing ships are more complicated to automate than on cargo ships, which may prove to be an important reason not to invest in autonomous technology to replace the crew on these ships.

Since in scenarios 1, 2 and 3 the damage to the ship and her cargo is assumed to remain unchanged, only a reduction in the loss of life will be present for these cases. For scenarios 4, 5 and 6 the effects of smart autonomous navigation are assessed, without a significant reduction in crew size on the affected ship. This leads to fewer navigation-related incidents which in turn leads to a reduction in the loss of life and a reduction in the number of ships lost.

## 3. Results of the casualty analysis

This section first discusses the fleet at risk in the period 2000–2018. Thereafter, the accident statistics per accident category are presented, followed by the accident statistics per ship size. Last, the accident statistics considering only navigation-related accidents are presented.

### 3.1. Fleet at risk

This section provides an overview of the composition of the world fleet over the analysed period, i.e. 2000–2018, based on the data in the IHS SeaWeb® database. The fleet is represented by shipyears; i.e. a ship that was in operation during the entire period accounts for 19 shipyears.

Fig. 1 shows the development of the world fleet over the period 2000–2018. In this period it has become significantly larger. As a result, the number of ships at risk have increased significantly and the sea has become busier than ever before.

Furthermore, Fig. 1 shows that roughly half of the fleet are merchant vessels (excluding ships intended to carry passengers). The other half consists for a large part of tugs (64% of the category ‘miscellaneous’) and regular fishing vessels (94% of the category ‘fishing’).

Fig. 2 shows the distribution in size per ship type. The following is observed from the fleet data:

- General cargo/multipurpose ships are found in the lower half of the size range, none of which are longer than 200 m.
- Bulk carriers tend to be larger than 160 m, but with a significant peak between 160 and 200 m, these are the so-called handymax ships. Furthermore, the second highest peak accounting for ships between 200 and 240 m is due to the maximum size for operation on the Great Lakes. The third highest peak between 280 and 320 m are the Panamax ships.
- Container ships are more evenly distributed from 120 meter to the largest existing ships.
- Tankers exist in all sizes, but with a significant number of smaller product tankers for local distribution of refined products, compared to the larger crude oil tankers.
- Other cargo ships are more evenly distributed and tend to be larger than general cargo/multipurpose ships, but not often larger than 200 m.
- ‘Miscellaneous’ is a broad category with ships of all sizes. Most of the smaller ships (64%) in this category are tugs.
- Offshore accounts for several different ship types from small diving support vessels to very large FSOs. The majority of this category are supply ships (50%) or anchor handling tugs (27%), which are also the smaller ships.

### 3.2. Statistics per accident category

The complete set of casualty records covers 14,887 serious shipping accidents. Fig. 3 provides a global overview of the casualty types that ships have been involved in.

As can be seen from Fig. 3, most recorded shipping accidents are ‘hull/machinery damage’, followed by ‘collision’ and ‘stranded’. The remaining casualty types occur significantly less often. Especially ‘missing’ and ‘war-loss/hostilities’ only occurred a few times between 2000 and 2018.

Furthermore, Fig. 3 shows that most shipping accidents involve general cargo/multipurpose ships.

In Fig. 4, the number of killed or missing persons per casualty type and ship type are presented. A total of 3306 lives have been lost in the period 2000–2018. The figure does not distinguish between lives lost on ships that were lost and on ships that survived the accident. However, the underlying data shows that 83% of the fatalities are associated with ships that were lost due to the accident. The only exceptions are fire/explosion accidents, for which only 42% of the fatalities are associated with ships that were lost due to the accident.

Fig. 4 also shows that most lives are lost during accidents involving collision, fire/explosion, foundering and hull/machinery damage. As can be seen in Fig. 3, these are not necessarily the casualty types that occur most often. Especially the categories ‘foundered’ and ‘stranded’ stand out. Foundering occurs less often than other categories but is still the second largest cause for loss of life. In contrast to ‘stranded’, which is

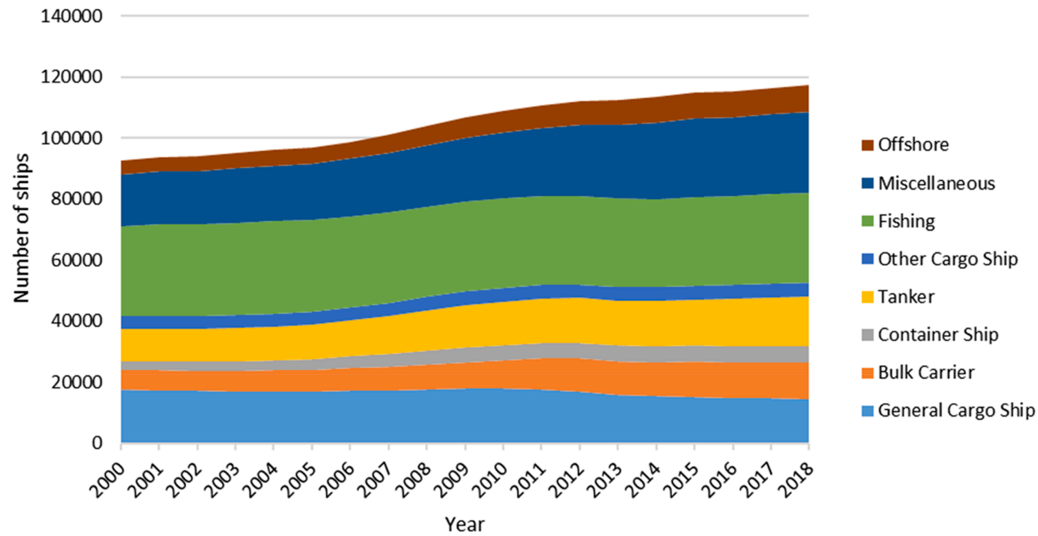



**Fig. 1.** Fleet at risk per ship type per year.

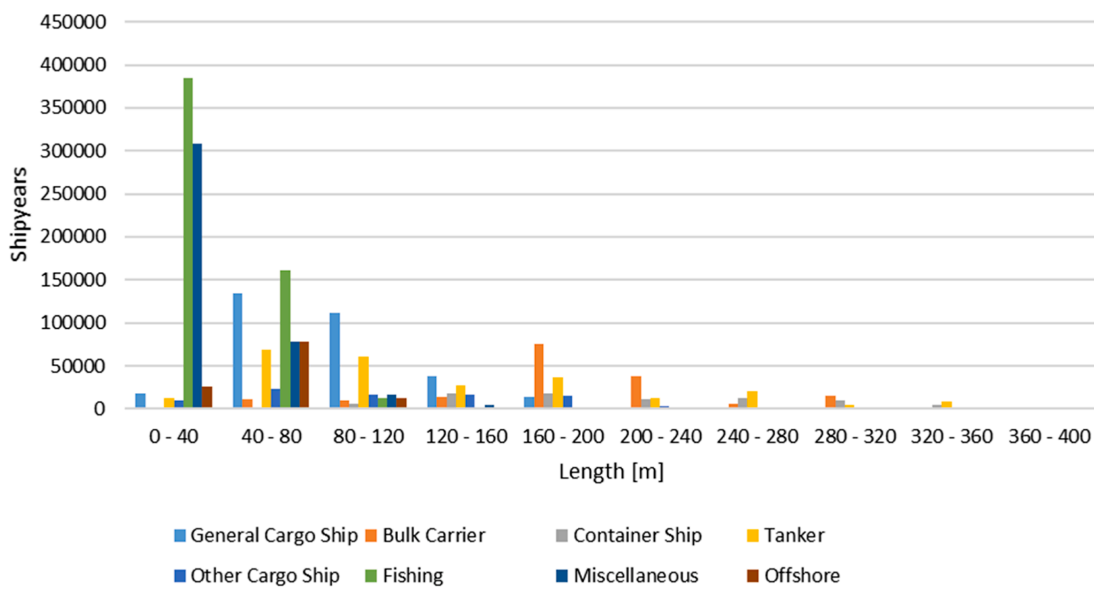



**Fig. 2.** Fleet at risk per ship type and size.

the third most occurring casualty type, but does not lead to large numbers of lives lost.

The fact that a significant number of lives is lost during foundering accidents, can be explained by the definition of the category 'foundered'. For a ship to be foundered, it must sink, often due to heavy weather. The circumstances of such an accident can drastically decrease the ability of the crew to save themselves. Stranding accidents result in a ship loss far less often. Also, the ship loss is not necessarily due to sinking; the ship can also be declared as lost due to the damage it took during the stranding accident. Therefore, the circumstances during stranding accidents are more likely to allow the crew to bring themselves to safety.

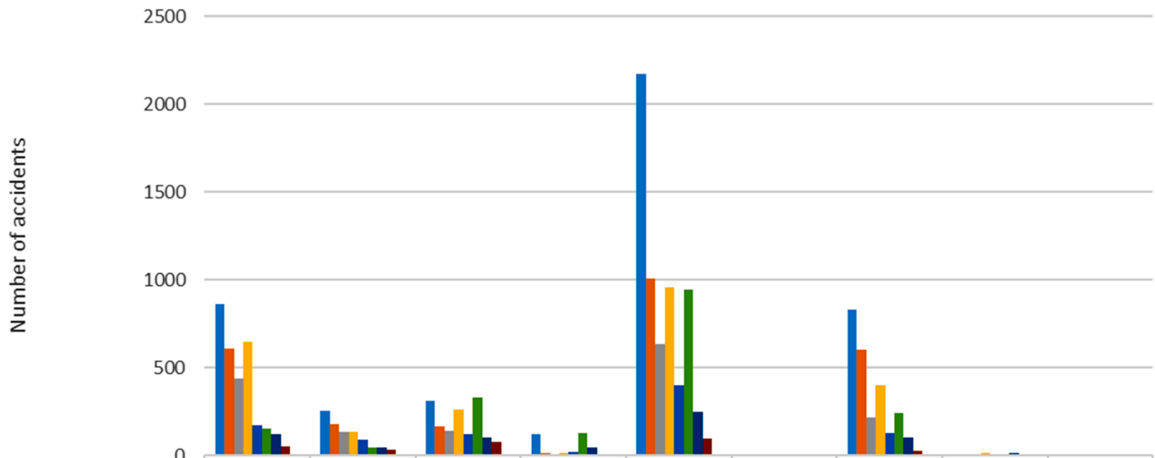
Although Fig. 4 does not show this explicitly, most of the lives lost allocated to 'hull/machinery damage' are associated with accidents where the ship subsequently foundered. This is of importance, because it shows that in general most lives are lost when the ship takes water and subsequently sinks. The exceptions to this statement are the fire/explosion accidents, where the fire and explosion events itself contribute to the risk of losing lives.

Fig. 4 also shows that most lives are lost on general cargo/multipurpose ships, which can be expected, since most recorded shipping accidents involve general cargo/multipurpose ships. However, the lives lost during collision accidents is disproportionally large compared to other ship types involved in collisions. Therefore, collision accidents are more deadly for crew on general cargo/multipurpose ships. This can also be seen in Fig. 5, which shows that general cargo/multipurpose ships sink far more often as a result of a collision compared to other ship types.

Fishing ships account for the second largest number of lives lost. Although fishing ships are one of the most common ship types, the number of shipping accidents is lower compared to cargo ships. As a result, it appears that shipping accidents involving fishing ships are more deadly for the crew, which may at least partially be attributed to their size.

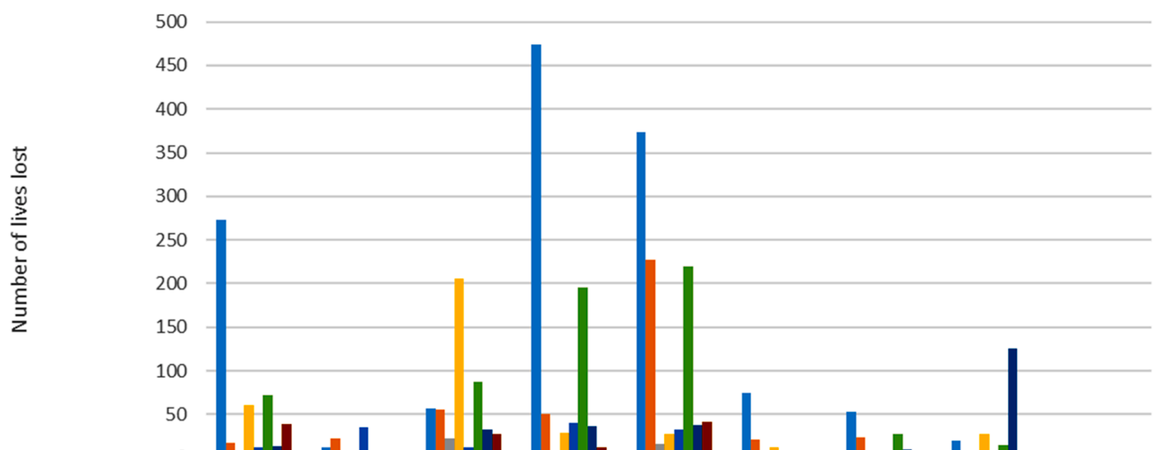
Furthermore, it can be seen that for tankers, the most lives are lost during fire/explosion accidents. It can be expected that fire/explosion accidents are more severe on tankers since these ships generally transport flammable substances.

The lives lost on miscellaneous ships during war-loss/hostilities



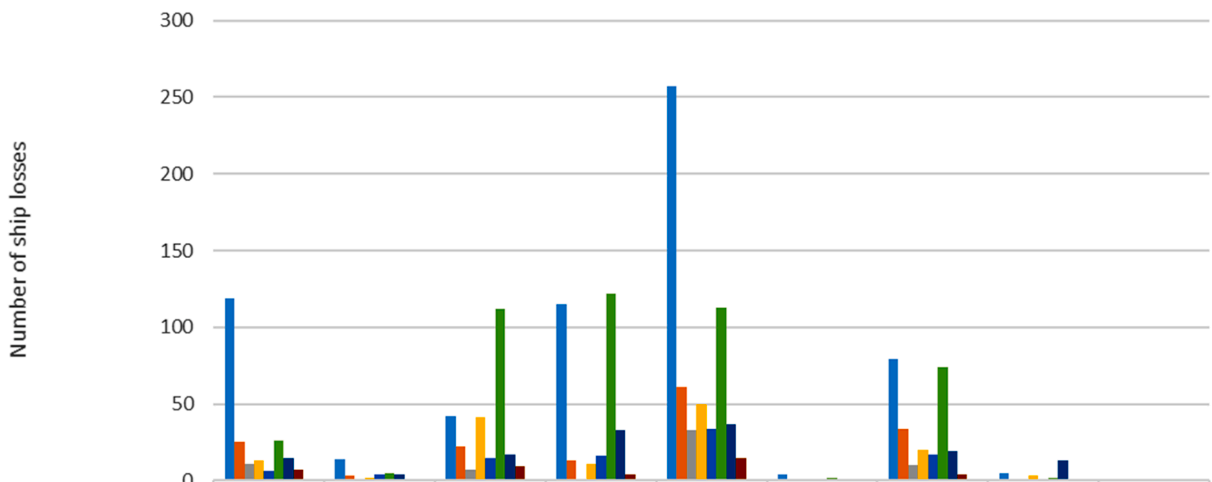

| | Collisions | Contact | Fire / Explosion | Foundered | Hull / Machinery Damage | Missing | Stranded | War-loss / Hostilities | Total |
|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 865 | 256 | 310 | 120 | 2173 | 5 | 829 | 6 | 4564 |
| Bulk Carrier | 607 | 181 | 164 | 15 | 1007 | 1 | 604 | 3 | 2582 |
| Container Ship | 439 | 136 | 143 | 0 | 633 | 0 | 215 | 0 | 1566 |
| Tanker | 648 | 136 | 263 | 16 | 956 | 3 | 401 | 13 | 2436 |
| Other Cargo Ship | 174 | 87 | 121 | 19 | 400 | 0 | 130 | 1 | 932 |
| Fishing | 151 | 43 | 330 | 129 | 945 | 2 | 241 | 2 | 1843 |
| Miscellaneous | 124 | 43 | 104 | 43 | 245 | 3 | 101 | 16 | 679 |
| Offshore | 52 | 32 | 75 | 4 | 93 | 0 | 27 | 2 | 285 |
| Total | 3060 | 914 | 1510 | 346 | 6452 | 14 | 2548 | 43 | 14887 |

**Fig. 3.** Number of serious shipping accidents per ship type and accident category.




| | Collisions | Contact | Fire / Explosion | Foundered | Hull / Machinery Damage | Missing | Stranded | War-loss / Hostilities | Total |
|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 273 | 13 | 57 | 474 | 374 | 75 | 53 | 20 | 1339 |
| Bulk Carrier | 18 | 22 | 55 | 50 | 227 | 21 | 24 | 0 | 417 |
| Container Ship | 4 | 2 | 22 | 0 | 16 | 0 | 1 | 0 | 45 |
| Tanker | 61 | 0 | 206 | 29 | 28 | 12 | 0 | 27 | 363 |
| Other Cargo Ship | 12 | 35 | 13 | 40 | 33 | 0 | 1 | 0 | 134 |
| Fishing | 72 | 1 | 87 | 195 | 220 | 6 | 28 | 15 | 624 |
| Miscellaneous | 14 | 3 | 33 | 37 | 38 | 1 | 10 | 126 | 262 |
| Offshore | 39 | 0 | 28 | 13 | 42 | 0 | 0 | 0 | 122 |
| Total | 493 | 76 | 501 | 838 | 978 | 115 | 117 | 188 | 3306 |

**Fig. 4.** Number of lives lost per ship type and accident category.




| | Collisions | Contact | Fire / Explosion | Foundered | Hull / Machinery Damage | Missing | Stranded | War-loss / Hostilities | Total |
|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 119 | 14 | 42 | 115 | 257 | 4 | 79 | 5 | 635 |
| Bulk Carrier | 25 | 3 | 22 | 13 | 61 | 1 | 34 | 0 | 159 |
| Container Ship | 11 | 1 | 7 | 0 | 33 | 0 | 10 | 0 | 62 |
| Tanker | 13 | 2 | 41 | 11 | 50 | 1 | 20 | 3 | 141 |
| Other Cargo Ship | 6 | 4 | 15 | 16 | 34 | 0 | 17 | 0 | 92 |
| Fishing | 26 | 5 | 112 | 122 | 113 | 2 | 74 | 2 | 456 |
| Miscellaneous | 15 | 4 | 17 | 33 | 37 | 1 | 19 | 13 | 139 |
| Offshore | 7 | 1 | 9 | 4 | 15 | 0 | 4 | 0 | 40 |
| Total | 222 | 34 | 265 | 314 | 600 | 9 | 257 | 23 | 1724 |

**Fig. 5.** Number of ship losses per accident category and ship type.

accidents stands out as well. All lost lives are associated with patrol vessels owned by the government of Sri Lanka.

Fig. 5 shows the ship losses per accident category. Most ship losses are associated with general cargo/multipurpose ships and fishing vessels. A total of 1724 ships have been lost in the period 2000–2018.

Fig. 5 shows some similarities with Fig. 4. Most ships that were lost are general cargo/multipurpose ships and fishing ships. It is noteworthy that general cargo/multipurpose ships sink more often than other cargo ships. The probability that a ship is lost due to an accident is twice as high for general cargo/multipurpose ships as for other cargo ships. Regarding fishing ships, 25% of the shipping accidents resulted in a ship loss, the highest probability of all ship types.

Furthermore, it appears that fire/explosion and stranded accidents cause significantly more ship losses for fishing ships compared to other ship types. Container ships, on the other hand, have a better track record of surviving a fire/explosion accident compared to other ship types.

### 3.3. *Statistics per ship size category*

Fig. 6 shows the number of shipping accidents as a function of the length of the ship and the ship type. The trend of the figure can mostly be explained by the number of ships that were in operation for each length interval from 2000 to 2018, as shown in Fig. 2. The most remarkable observation is that the large number of small fishing and miscellaneous ships that are in operation are not proportionally represented in Fig. 6.

Regarding cargo ships, Fig. 6 is more in line with the number of ships that were in operation. Most general cargo/multipurpose ships had a length between 80 and 120 m. The number of ships decreases steadily when the ships become larger, with an exception for ships between 160 and 200 m. Another peak is present for this interval, because of an increased number of bulk carriers that are able to access most smaller ports, so-called handymax ships. The interval that stands out most is the interval from 40 to 80 m. The number of general cargo/multipurpose ships at risk for this length interval is close to the number of ships of the interval 80 to 120 m. However, for ships between 40 and 80 m significantly fewer shipping accidents have been reported. This may suggest significant underreporting of shipping accidents for ships under 80 m.

In general, most shipping accidents occur with ships having a length below 200 m. Moreover, these are also the most severe shipping accidents. Fig. 7 shows the historic frequency of a total ship loss when involved in a given type of shipping accident. It follows that the highest probabilities that the ship is lost occur for ships of under 200 m in length and increase as ships get smaller.

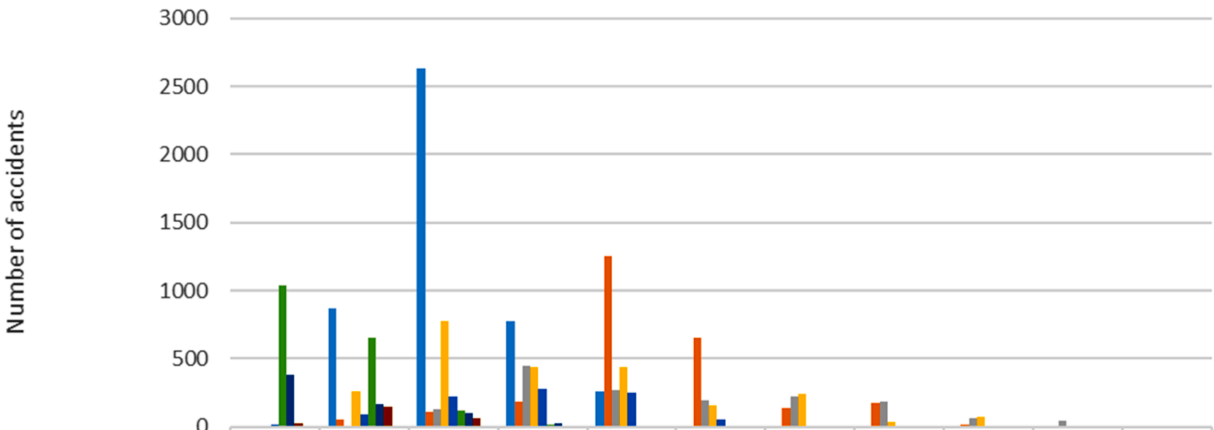
Fig. 8 shows the number of lives lost per ship size and type. 76% of all lives lost are on ships under 120 m. Most of these lives are lost on general cargo/multipurpose ships.

Regarding the larger ships, most lives are lost on bulk carriers. However, these numbers can mostly be allocated to a few accidents where the entire crew died due to the accident. The crew size of large bulk carriers is around 30, which means that two or three severe accidents can already account for more than 50 fatalities.

### 3.4. *Navigation-related accidents*

In this section more details are provided on the accident statistics of navigation-related accidents. The results of this section are used to find the safety benefit for the scenarios where it is assumed that autonomous ships will be involved in fewer navigation-related accidents due to an autonomous navigation system. Navigation-related accidents consist of collision, contact and stranding accidents.

Fig. 9 shows the number of navigation-related accidents per ship size and type. In total 6522 navigation-related accidents occurred between




| | 0 - 40 | 40 - 80 | 80 - 120 | 120 - 160 | 160 - 200 | 200 - 240 | 240 - 280 | 280 - 320 | 320 - 360 | 360 - 400 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 11 | 873 | 2631 | 780 | 260 | 9 | 0 | 0 | 0 | 0 | 4564 |
| Bulk Carrier | 0 | 55 | 114 | 184 | 1253 | 650 | 136 | 175 | 13 | 2 | 2582 |
| Container Ship | 0 | 4 | 126 | 452 | 272 | 197 | 225 | 183 | 66 | 41 | 1566 |
| Tanker | 8 | 260 | 774 | 437 | 438 | 162 | 246 | 39 | 72 | 0 | 2436 |
| Other Cargo Ship | 20 | 90 | 228 | 283 | 249 | 53 | 9 | 0 | 0 | 0 | 932 |
| Fishing | 1042 | 657 | 122 | 20 | 2 | 0 | 0 | 0 | 0 | 0 | 1843 |
| Miscellaneous | 379 | 167 | 100 | 29 | 2 | 2 | 0 | 0 | 0 | 0 | 679 |
| Offshore | 31 | 151 | 68 | 12 | 2 | 5 | 9 | 1 | 6 | 0 | 285 |
| Total | 1491 | 2257 | 4163 | 2197 | 2478 | 1078 | 625 | 398 | 157 | 43 | 14887 |

Ship length [m]

**Fig. 6.** Number of shipping accidents per ship type and size.

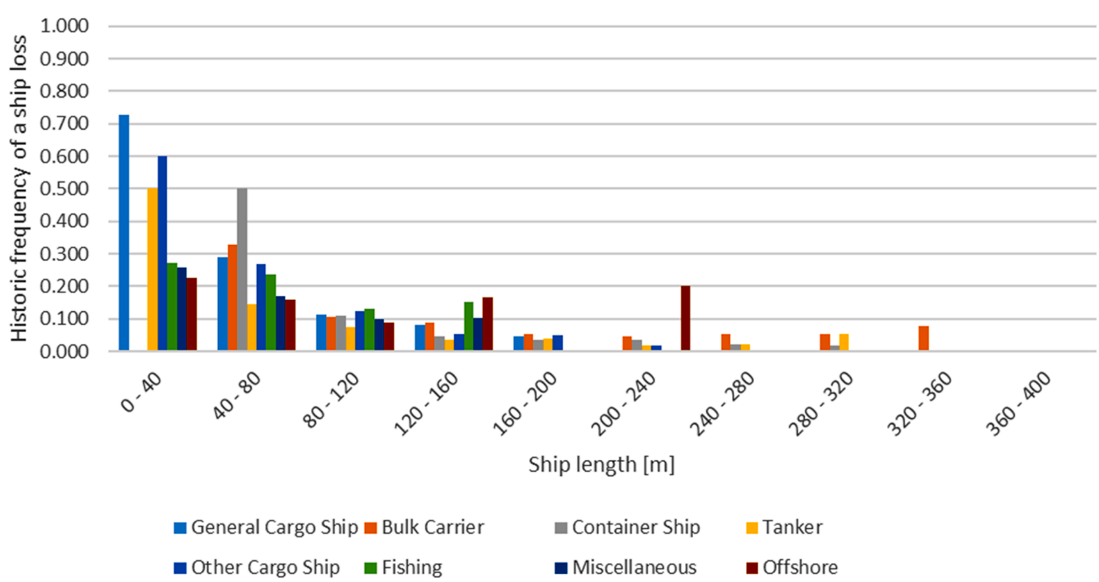
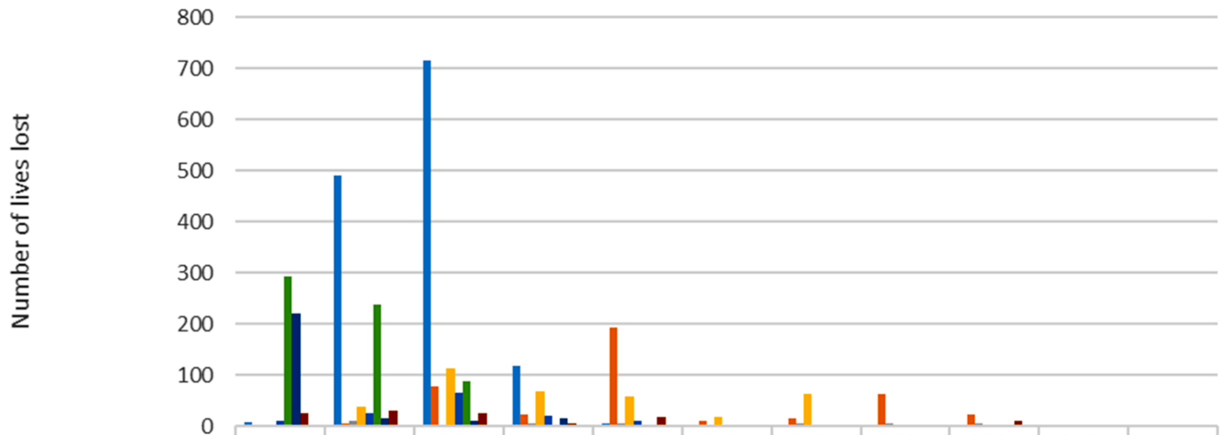



**Fig. 7.** Historic frequency of ship loss per accident sorted by length of the ship involved and ship type.

2000 and 2018. Therefore, navigation-related accidents account for 44% of all accidents in the dataset.

The distribution is similar to that in Fig. 6. The only significant difference that can be noticed is that the number of navigation-related accidents for fishing ships is lower, compared to other ship types. For fishing ships less than 25% of the shipping accidents are navigation-related. This difference is mostly explained by a low number of collision accidents. This might be explained by the fact that fishing ships spent more time in less crowded fishing areas and less time in busy traffic lanes, where the probability of a collision is higher.

Fig. 10 shows the number of ship losses due to navigation-related accidents. The total number of ship losses due to navigation-related accidents between 2000 and 2018 is 513, which is only 30% of all ship losses. This implies that navigation-related accidents are on average less severe than other casualty types in terms of damage to the ship. As can be seen, the number of ship losses rapidly decreases for ships with a




| | 0 - 40 | 40 - 80 | 80 - 120 | 120 - 160 | 160 - 200 | 200 - 240 | 240 - 280 | 280 - 320 | 320 - 360 | 360 - 400 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 9 | 490 | 715 | 118 | 7 | 0 | 0 | 0 | 0 | 0 | 1339 |
| Bulk Carrier | 0 | 7 | 79 | 24 | 193 | 12 | 15 | 64 | 23 | 0 | 417 |
| Container Ship | 0 | 11 | 2 | 6 | 6 | 2 | 5 | 7 | 5 | 1 | 45 |
| Tanker | 0 | 38 | 114 | 69 | 58 | 18 | 63 | 0 | 3 | 0 | 363 |
| Other Cargo Ship | 10 | 27 | 66 | 21 | 10 | 0 | 0 | 0 | 0 | 0 | 134 |
| Fishing | 294 | 237 | 89 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 624 |
| Miscellaneous | 221 | 15 | 11 | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 262 |
| Offshore | 26 | 32 | 25 | 5 | 19 | 3 | 1 | 0 | 11 | 0 | 122 |
| Total | 560 | 857 | 1101 | 262 | 293 | 35 | 84 | 71 | 42 | 1 | 3306 |

Ship length [m]

**Fig. 8.** Number of lives lost per ship type and size.

length above 120 m. This can at least in part be attributed to IMO's damage stability regulations. The required subdivision index that is used in the SOLAS regulations is dependent on the length of the ship: as ships get longer, the index rises, thus requiring the ship to stay afloat in a larger number of damage scenarios.

Fig. 11 shows the number of lives lost during navigation-related accidents. The total number of lives lost due to such accidents is 686, which is only 21% of all lives lost between 2000 and 2018. This implies that in terms of loss of life, navigation-related accidents are on average less severe than other casualty types.

Equivalent to the ship losses, most lives are lost on ships below 120 m as well. A notable exception is the accident involving the large crude oil tanker Sanchi, which caught fire after the collision which caused the death of the entire crew of 32.

Compared to Fig. 8, the difference between small and large ships is even larger for navigation-related accidents. Almost 90% of all lives lost are associated with ships under 120 m. General cargo/multipurpose ships account for almost half of the fatalities.

## 4. Evaluation of autonomous shipping scenarios

Since the distribution of lives lost and ships lost over different accident types, ship types and ship sizes are now known, it is possible to assess the impact of the autonomous shipping scenarios presented in section 2.4, under the assumption that the only affected incident types are those that are related to navigation. As discussed in section 2.2 we assume that the regulatory demand for equivalent safety will prevent the large-scale market entry of ships that have a higher risk of non-navigation-related incidents. This section focusses on quantifying the effects of an implementation scenario, while the meaning of these results is discussed in section 5. An overview of the effects of each scenario can be found in table 2 in section 4.7.

### *4.1. Small cargo ships become unmanned*

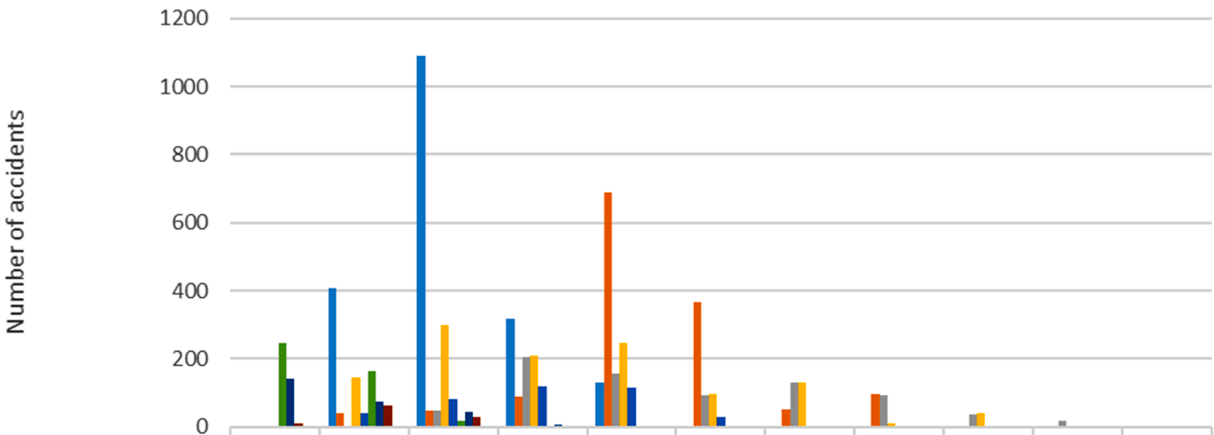
Small cargo ships (ships under 120 meter) represent 23% of the fleet under consideration, derived from Fig. 2. In this scenario, small cargo ships will become unmanned due to the implementation of autonomous systems. The realization of this scenario will reduce the number of lives lost by 47.4%, based on the numbers in Fig. 8. Three-quarters of this reduction will be realized by removing the crew from general cargo/multipurpose ships. A reduction of 47.4% in loss of life comes down to a reduction of 83 lives lost per year.

### *4.2. All cargo ships become unmanned*

All cargo ships together represent 50% of the fleet, derived from Fig. 2. In this scenario all cargo ships will become unmanned due to the implementation of autonomous systems. The realization of this scenario will further reduce the number of lives lost at sea, to a total reduction of 69.5%, based on the numbers in Fig. 8. Almost half of the extra reduction in this scenario compared to the first scenario will be realized by removing crew from bulk carriers. A reduction of 69.5% in loss of life comes down to a reduction of 121 lives lost per year.

### *4.3. All ships become unmanned*

In the third scenario, the entire fleet will become unmanned due to the implementation of autonomous systems. As a result, no more lives will be lost at sea. The majority of the extra lives that will be saved compared to scenario 2 will be realized by removing crew from tugs and fishing vessels. The removal of the crew from all ships comes down to a




| | 0 - 40 | 40 - 80 | 80 - 120 | 120 - 160 | 160 - 200 | 200 - 240 | 240 - 280 | 280 - 320 | 320 - 360 | 360 - 400 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 5 | 407 | 1089 | 317 | 130 | 2 | 0 | 0 | 0 | 0 | 1950 |
| Bulk Carrier | 0 | 42 | 48 | 91 | 690 | 368 | 51 | 97 | 4 | 1 | 1392 |
| Container Ship | 0 | 1 | 50 | 207 | 157 | 93 | 129 | 95 | 38 | 20 | 790 |
| Tanker | 5 | 145 | 301 | 208 | 245 | 96 | 132 | 12 | 41 | 0 | 1185 |
| Other Cargo Ship | 4 | 40 | 82 | 121 | 114 | 28 | 2 | 0 | 0 | 0 | 391 |
| Fishing | 247 | 165 | 20 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 435 |
| Miscellaneous | 141 | 74 | 45 | 7 | 0 | 1 | 0 | 0 | 0 | 0 | 268 |
| Offshore | 12 | 64 | 28 | 3 | 0 | 2 | 1 | 0 | 1 | 0 | 111 |
| Total | 414 | 938 | 1663 | 957 | 1336 | 590 | 315 | 204 | 84 | 21 | 6522 |

Ship length [m]

**Fig. 9.** Number of navigation-related accidents per ship size and type.

reduction of 174 lives lost per year.

### 4.4. Reduced number of accidents for small cargo ships

In this scenario the implementation of autonomous systems will again be limited to small cargo ships, just like in scenario 1. However, in this scenario, it is assumed that the number of navigation-related accidents for small cargo ships will be reduced, but that the number of crew on board will remain the same. As mentioned before, small cargo ships (under 120 m) represent 23% of the fleet, derived from Fig. 2.

The maximum safety benefit can be realized by eliminating all the navigation-related accidents for these ships. This would result in a reduction in the total number of ships lost by 14.2%, based on Fig. 5 and Fig. 10, which comes down to saving 13 ships per year. The total number of lives lost at sea will be reduced by 12.8%, based on Fig. 4 and Fig. 11, which comes down to saving 22 lives per year.

The actual benefit that can be associated with this scenario depends on the percentage of navigation-related accidents that can be prevented by automation. A reduction of 0% will, obviously, result in no reduction in ship losses or lives lost. A reduction of 100% will lead to the reductions as mentioned above. Any other reduction in navigation-related accidents between 0% and 100% will result in a corresponding reduction in ship losses and lives lost. As an example, a reduction of 50% in navigation-related accidents, will result in a reduction of 7.1% in ship losses.

### 4.5. Reduced number of accidents for all cargo ships

In this scenario the implementation of autonomous systems will also affect the remaining cargo ships. In other words, it is assumed that the number of navigation-related accidents will be reduced for all cargo ships. As mentioned before, all cargo ships represent 50% of the fleet, as derived from Fig. 2.

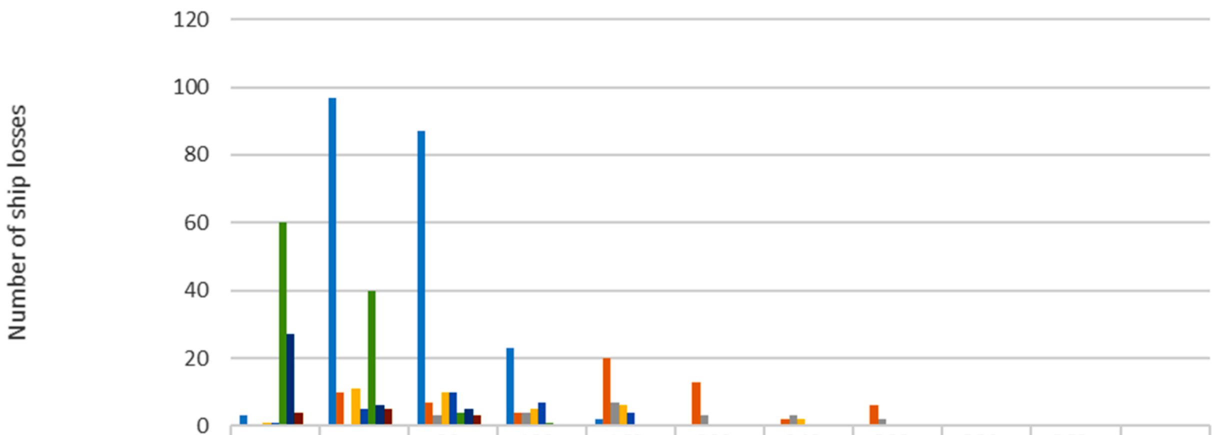
The maximum safety benefit can be realized by eliminating all navigation-related accidents for these ships. This would result in a reduction in the total number of ships lost with 20.8%, based on Fig. 5 and Fig. 10, which comes down to saving 19 ships per year. The total number of lives lost at sea will be reduced by 15.7%, based on Fig. 4 and Fig. 11, which comes down to saving 27 lives per year.

Again, the actual safety benefit will depend on the percentage of navigation-related accidents that can be prevented by automation. Therefore, the reduction in ship losses and lives lost will be anywhere between no benefit and the maximums as mentioned above, equivalent to the reduction in navigation-related accidents.

### 4.6. Reduced number of accidents for all ships

In the final scenario, the entire fleet will become autonomous. Moreover, it is assumed that the implementation of autonomous systems will reduce the number of navigation-related accidents for all ships. The realization of this scenario will result in a maximum safety benefit if all navigation-related accidents can be prevented. This would result in a decrease of ship losses by 29.8%, based on Figs. 5 and 10, which comes down to saving 27 ships per year. Furthermore, the total number of lives lost at sea will be reduced by 20.8%, based on Figs. 4 and 11, which comes down to saving 36 lives per year.

Once more, the actual safety benefit will depend on the percentage of navigation-related accidents that can be prevented by automation. Therefore, the reduction in ship losses and lives lost will be anywhere between no benefit and the maximums as mentioned above, equivalent to the reduction in navigation-related accidents.




| | 0 - 40 | 40 - 80 | 80 - 120 | 120 - 160 | 160 - 200 | 200 - 240 | 240 - 280 | 280 - 320 | 320 - 360 | 360 - 400 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 3 | 97 | 87 | 23 | 2 | 0 | 0 | 0 | 0 | 0 | 212 |
| Bulk Carrier | 0 | 10 | 7 | 4 | 20 | 13 | 2 | 6 | 0 | 0 | 62 |
| Container Ship | 0 | 0 | 3 | 4 | 7 | 3 | 3 | 2 | 0 | 0 | 22 |
| Tanker | 1 | 11 | 10 | 5 | 6 | 0 | 2 | 0 | 0 | 0 | 35 |
| Other Cargo Ship | 1 | 5 | 10 | 7 | 4 | 0 | 0 | 0 | 0 | 0 | 27 |
| Fishing | 60 | 40 | 4 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 105 |
| Miscellaneous | 27 | 6 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 38 |
| Offshore | 4 | 5 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 |
| Total | 96 | 174 | 129 | 44 | 39 | 16 | 7 | 8 | 0 | 0 | 513 |

Ship length [m]

**Fig. 10.** Number of ship losses during navigation-related accidents per ship type and size.

### 4.7. Summary

In Table 2 a summary of the results of this section is presented. The first column denotes the scenario under consideration, presented in the order in which they have been discussed in this section. The second column shows the percentage of the fleet under consideration that will be affected in that scenario. The third and fourth columns show the reduction in ship losses that the scenario will induce. The fifth and sixth columns show the reduction in loss of life that the scenario will induce.

## 5. Summary and discussion

In section 3 the shipping accidents between 2000 and 2018 have been evaluated for cargo carrying ships, fishing ships and service ships. First, this analysis showed that the most severe accidents are those where water ingress occurs, whether the source is known (such as collision accidents) or not (foundering accidents). The majority of lives lost and ships lost are associated with these types of shipping accidents. The second most important cause for loss of life and loss of ship are fire accidents.

Moreover, section 3.4 showed that even though navigation-related accidents account for 44% of all shipping accidents, only 30% of the ship losses and 21% of the lives lost are associated with these types of accidents.

Furthermore, section 3.3 showed that most accidents are associated with smaller ships of under 120 meter in length. For these ships, the probability of a ship loss as a result of the accident is higher and 76% of all lives lost can be allocated to ships shorter than 120 m. This over-representation of small ships is not unexpected, since it is accepted that their chance of surviving an incident is smaller than that of larger ships. This is e.g. expressed in the required subdivision index in IMO's SOLAS regulations. The value of this index increases with ship length.

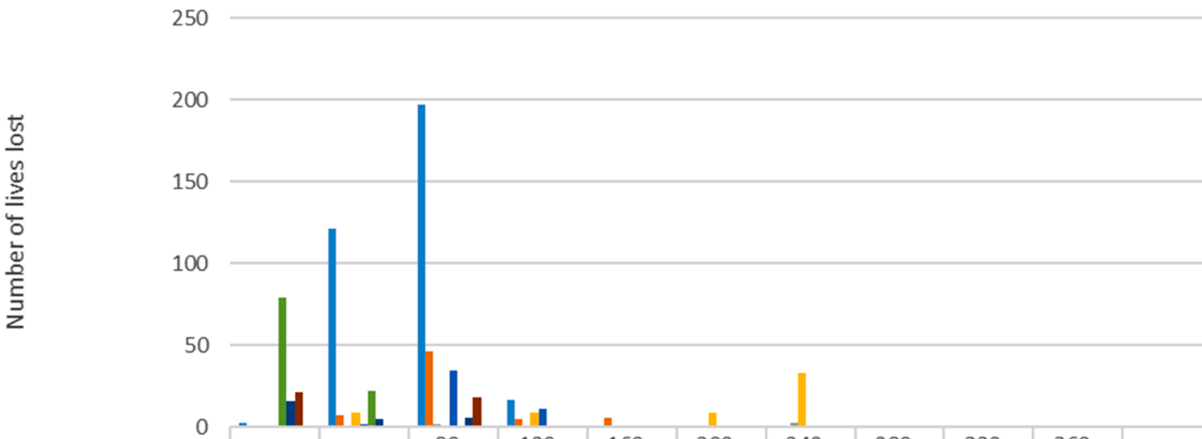
For the majority of the accidents associated with smaller ships, the ship that is involved is a general cargo/multipurpose ship.

The increase in safety has been evaluated for six different scenarios in section 4. A summary of the results can be found in Table 2 in section 4.7. These scenarios differ from each other in two ways (see section 2.3). The first difference is whether autonomous ships will lead to completely unmanned ships or to a decrease in navigation-related accidents. The second difference is which ships will become autonomous or unmanned.

First, section 4 showed that the safety benefit of autonomous ships will be largest for small cargo ships. Small cargo ships represent 23% of the fleet considered in this article. Regardless of the ships becoming unmanned or the ships being involved in less navigation-related accidents, small cargo ships already account for half of the potential safety benefit of the fleet under consideration.

In scenarios 1, 2 and 3 the safety benefit is evaluated if ships will become unmanned due to the implementation of autonomous systems. Almost 50% of all lives lost are associated with small cargo ships. To prevent the loss of the remaining 50%, larger cargo ships, service ships and fishing ships will have to become unmanned as well. On service ships, fishing ships and larger cargo ships the crew size is generally larger than on small cargo ships and, therefore, the investment to make these ships unmanned can be expected to be larger than for small cargo ships. Furthermore, on service ships and fishing ships, several tasks performed by the crew might be too complex to be performed by a machine [33]. Thus, especially for service ships and fishing ships it can be a challenge to remove the crew.

The assumption that full autonomy may be limited to smaller ships is supported by the CEO of Maersk, Søren Skou, who has expressed that he does not expect that large container ships will become autonomous anytime soon [34]. Regarding the added safety benefit of large autonomous container ships, the impact of removing the crew will be small, since there are only few lives lost on container ships in general.




| | 0 - 40 | 40 - 80 | 80 - 120 | 120 - 160 | 160 - 200 | 200 - 240 | 240 - 280 | 280 - 320 | 320 - 360 | 360 - 400 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| General Cargo Ship | 3 | 121 | 197 | 17 | 1 | 0 | 0 | 0 | 0 | 0 | 339 |
| Bulk Carrier | 0 | 7 | 46 | 5 | 6 | 0 | 0 | 0 | 0 | 0 | 64 |
| Container Ship | 0 | 0 | 2 | 1 | 0 | 0 | 3 | 1 | 0 | 0 | 7 |
| Tanker | 0 | 9 | 1 | 9 | 0 | 9 | 33 | 0 | 0 | 0 | 61 |
| Other Cargo Ship | 0 | 2 | 35 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 48 |
| Fishing | 79 | 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 101 |
| Miscellaneous | 16 | 5 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 27 |
| Offshore | 21 | 0 | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 39 |
| Total | 119 | 166 | 305 | 43 | 7 | 9 | 36 | 1 | 0 | 0 | 686 |

**Fig. 11.** Number of lives lost during navigation-related accidents per ship type and size.

**Table 2**
A summary of the evaluation of each scenario.

| Scenario | Percentage of the fleet that is affected | Reduction in ship losses | | Reduction in lives lost | |
|---|---|---|---|---|---|
| | | Percentage | Ships saved per year | Percentage | Lives saved per year |
| 1 – small cargo ships become unmanned | 23% | n/a | n/a | 47.4% | 83 |
| 2 – all cargo ships become unmanned | 50% | n/a | n/a | 69.5% | 121 |
| 3 – all ships become unmanned | 100% | n/a | n/a | 100% | 174 |
| 4 – reduced number of accidents for small cargo ships | 23% | 0% – 14.2% | 0 – 13 | 0% – 12.8% | 0 – 22 |
| 5 – reduced number of accidents for cargo ships | 50% | 0% – 20.8% | 0 – 19 | 0% – 15.7% | 0 – 27 |
| 6 – reduced number of accidents for all ships | 100% | 0% – 29.8% | 0 – 27 | 0% – 20.8% | 0 – 36 |

Therefore, the added safety benefit would not be a good reason to invest in (large) autonomous container ships, supporting the expectation of Skou.

Scenarios 4, 5 and 6 assume that autonomy will decrease the number of navigation-related accidents. Furthermore, as discussed in section 2.2, it is assumed that other incident types are not affected. As mentioned in section 3.4, navigation-related accidents account for 44% of all serious shipping accidents, 30% of all ship losses and 21% of all lives lost. Therefore, the largest possible safety benefit for these scenarios would be a decrease of 30% of the total number of ship losses and a decrease of 21% in the total number of lives lost. However, in order to achieve this result, autonomous systems would need to be flawless in terms of navigation, such that there no longer will be navigation-related accidents. As described in section 2.4, for the scenarios in this article the possible safety benefit is given as a range between no benefit and the maximum possible benefit, corresponding to respectively no reduction in navigation-related accidents and a reduction of 100% in navigation-related accidents. Half of these reductions can already be realised if only small cargo ships will become autonomous.

Concluding the evaluation of these three scenarios, although nearly half of the accidents at sea are navigation-related, these are not the most severe accidents. It remains uncertain which percentage of the navigation-related accidents might be prevented due to the introduction of autonomous navigation. The reduction of navigation-related accidents may be anywhere between 0% or 100%. Therefore, the reductions as presented in Table 2 are given as a range as well.

Comparing the first three scenarios with the second three scenarios, both sets show a noticeable improvement in safety. The number of shipping accidents at sea may be decreased through autonomous navigation and lives will be saved, assuming that autonomous systems are indeed able to reduce the number of accidents. However, making ships unmanned will lead to a significantly larger reduction in the number of lives lost at sea. We, therefore, have great appreciation for all effort that is put in the development of autonomous navigation systems, but, given the fact that autonomous navigation alone only removes a few people from the ship, we also highlight that there are further significant safety improvements to be gained by putting more effort in research that enables safe elimination of the crew's role in all other functions of the ship. In this research, specific emphasis should be placed on the increase of safety-by-design, since the crew will no longer be there to resolve problems that occur.

## CRediT authorship contribution statement

**Jiri de Vos:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. **Robert G. Hekkenberg:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Osiris A. Valdez Banda:** Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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