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# Damage stability requirements for autonomous ships based on equivalent safety

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ABSTRACT

In recent years, a significant amount of research has been conducted on autonomous ships. Since it is assumed that these ships will sail with a significantly reduced crew or even without people on board, the design of the ship needs reconsideration. The absence of people on board and the associated safety measures could result in a more efficient design, but amendments in the existing regulatory framework will be needed. In this article, we will focus on potential changes in the Convention for Safety Of Life At Sea (SOLAS) and in particular on the Required Subdivision Index. The index gives a requirement for the allowed probability of sinking when a ship is damaged due to collision. The evaluation is performed by using the principle of equivalent safety, which will ensure that unmanned ships will be at least as safe as manned ships. If the crew is no longer present, the consequences of an incident will be less severe, since the probability of casualties is no longer present. Consequently, a lower subdivision index might be accepted for unmanned autonomous ships. In this article, the damage stability-related level of risk of a manned ship will be derived by means of a risk analysis. Thereafter, the subdivision index for unmanned ships, which ensures an equivalent safety level to similar manned ships, is established for three individual ships. The assessment shows that a reduction in the subdivision index is allowed for unmanned ships and that the reduction will be largest for smaller ships.

## 1. Introduction

The research effort on autonomous ships has increased significantly over the last years. Several projects that explore the feasibility of autonomous ships have been launched, among them are the MUNIN project (MUNIN, 2016), the AAWA project (Rolls-Royce, 2016) and the YARA Birkeland demonstrator (Kongsberg, 2017). Besides these explorative projects, numerous projects address route planning and collision avoidance (Beser and Yildirim, 2018; Huang et al., 2020; Jeong et al., 2019; Ramos et al., 2019; Xue et al., 2019).

The realisation of an autonomous ship will enable a significant reduction in the crew size or even allow a ship to sail without people on board. The possibility to reduce the crew size can be used to counteract a shortage in well-trained personnel. It is predicted that there will be a need of 147,500 additional officers by 2025 (BIMCO and ICS, 2015). In a case study Kooij and Hekkenberg (2019) show that automating crew tasks can indeed reduce the crew size, but that careful consideration is needed in the decision which tasks to automate.

A second and important incentive for autonomous ships is economic efficiency, as it is for most innovations within the maritime industry (Karlis, 2018). Nevertheless, the business case of autonomous ships is still hard to make. Although there is a strong belief that autonomous ships would lead to more economic efficiency, only limited research has been performed in order to demonstrate what the overall effect of increased autonomy on transport costs would be (Frijters, 2017; Rødseth and Burmeister, 2015). More reductions in costs or improvement of transport performance for autonomous ships would make them more attractive and economically viable. Therefore, the design of the ship should be optimized for (unmanned) autonomous operations.

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

The International Maritime Organization (IMO) is currently

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performing a regulatory scoping exercise (RSE) (IMO, 2018a). The objective has been defined as, “to assess the degree to which the existing regulatory framework under its purview may be affected in order to address Maritime Autonomous Surface Ship (MASS) operations”. This is an important step in the development for autonomous ships, since the result of the RSE will provide insight into “how safe, secure and environmentally sound” MASS operations need to be.

Classification societies DNV GL and Lloyd’s Register already shared their belief in the need for a new regulatory framework for autonomous ships (Lloyd’s Register et al., 2017; Vartdal et al., 2018). This belief is shared by others from the shipping industry (Hooydonk, 2014; Karlis, 2018; Rolls-Royce, 2016). The development of a new regulatory framework would be the next step for IMO following the RSE. The classification societies have described what they believe the new regulatory framework should look like (Bureau Veritas, 2017; DNV GL, 2018; Lloyd’s Register, 2017), but the proposals remain of a qualitative nature. Only a limited amount of research is performed on the detailed definition of new regulations for autonomous ships. It is, however, adopted by all that the new regulations should ensure that autonomous ships will be as safe as manned ships.

The International Convention on the Safety Of Life At Sea (SOLAS) is a crucial document in the transition towards unmanned ships, since it provides important design requirements that should ensure the safety of the crew. However, the convention cannot be discarded all together, because it also covers, among others, risk to ship, cargo and people on nearby ships. Consequently, it has been suggested that the new legal framework for unmanned ships should fall under SOLAS (Hooydonk, 2014; Vartdal et al., 2018). Although a significant part of the SOLAS regulations will have to be amended to allow unmanned shipping, only the regulation concerning damage stability will be evaluated within this article. The reason that the regulation concerning damage stability will be evaluated is the expectation that any changes in this regulation will have the largest impact on the ship design. Also, it is expected that this can increase the economic efficiency of unmanned ships, since a reduction in the regulation concerning damage stability can increase the transport capacity of the ship (for the ships evaluated in this study, it has been verified with the original designers that the transport capacity is limited by the SOLAS damage stability regulations). Besides the economic benefits, this will also increase the external safety, since this will lead to less emissions per tonne of cargo transported.

As will be explained in Section 2.1, the primary requirement within the regulation concerning damage stability is called the required subdivision index. In this article the required subdivision index is evaluated and it is assessed for various ships how far this index could be lowered while still maintaining equivalent safety in case the crew is removed from the ship.

In Section 2 the method of the assessment is described. In Section 3 the consequences of a collision are quantified. In Section 4 three ships are analysed in an explorative quantification. The results of the assessment are presented along with a discussion of these results. In Section 5 the conclusions are presented. The recommendations follow in Section 6.

## 2. Method

In this section the method is described that is used to determine how far the required subdivision index can be lowered for unmanned ships. Before the actual assessment is described, the basics of probabilistic damage stability are explained in Section 2.1. In Section 2.2 the basics of safety and risk are explained. Combined with the theory from Section 2.1, Section 2.2 develops a damage stability-related risk analysis for manned ships. As a result a risk profile for a manned ship can be established. The level of risk of the same ship, but without a crew, will be lower, since the risk of losing life is eliminated. Within the procedure to find the allowable reduction in the required subdivision index, the overall level of risk of the unmanned ship will be changed such that it will become equivalent to the level of risk of the manned ship.

### 2.1. Probabilistic damage stability

Probabilistic damage stability is the overall method to evaluate a ship’s probability of survival, if the ship would be damaged in a collision[1]. This article focusses on cargo ships in general, for which the damage stability regulations are described in SOLAS (IMO, 2014). Besides the regulations in SOLAS, multiple other regulations exist both as alternatives or additions to the damage stability regulations in SOLAS. The study presented in this article will be limited to the evaluation of the regulations for cargo ships as described in SOLAS.

The primary requirement concerning damage stability is that the probability of survival of a ship has to be higher than a certain minimum value. Each ship has a property called the attained subdivision index, referred to as index A. IMO describes the index A as the total probability of survival, if the ship is damaged in a collision (IMO, 2017). The description has been adopted by, among others, Tuzcu (Tuzcu, 2003) and Papanikolaou & Eliopoulou (Papanikolaou and Eliopoulou, 2008). The primary requirement is represented by the required subdivision index, referred to as index R. In essence, for each ship the index A has to be higher than the index R. This will not change for unmanned ships. The index A will remain a property of unmanned ships and it will still need to be higher than a certain minimum value, the index R. However, within this article it is assessed if the index R can be lowered for unmanned ships.

For a full description on how to calculate index R and index A, the reader is referred to SOLAS Chapter II-1 Part B (IMO, 2014) and the accompanied explanatory notes (IMO, 2017). The necessary basics for this article are described below.

The probability of survival of a ship when damaged depends on many factors, which will be different for each ship and each individual trip. These factors are summarized by IMO (IMO, 2017) in the following five categories:

1. Which particular space or group of adjacent spaces is flooded;
2. The draught, trim and intact metacentric height at the time of damage;
3. The permeability of affected spaces at the time of damage;
4. The sea state at the time of damage;
5. Other factors such as possible heeling moments owing to unsymmetrical weights.

In order to account for these factors, the index A is broken down into the sum of the product of two probabilities, as is shown in Eq. (1). Subscript $i$ represents the damage zone (the particular space or group of adjacent spaces) under consideration. The value $p_i$ represents the probability that only damage zone $i$ will be flooded. The value $s_i$ represents the probability of survival after zone $i$ has been flooded. The summation denotes that the index A is calculated by evaluating the possible damage cases that follow from collision.

A damage case is a situation where one or more adjacent compartments are flooded. The actual damage that causes a damage cases has to be such that only these compartments will be flooded. Therefore, the size of the actual damage is given as a range. E.g. the length of the damage has to be long enough that all compartments are hit, but it cannot be longer than the overall length of the compartments. Similar ranges for the penetration depth and height of the damage are described by IMO. For each damage case, IMO prescribes a method to calculate the probability of occurrence for the specific damage case, denoted with $p_i$. This method is derived from a study on ship collisions (Lützen, 2001).

[1] Collision: striking or being struck by another ship (regardless of whether under way, anchored or moored.

Subsequently, for each damage case IMO prescribes a method to calculate the probability of survival after flooding, denoted with $s_i$. In order to make the concept practical, extensive simplifications have been used while incorporating the factors described above. Again, a full description of the calculation of $s_i$ can be found in SOLAS Chapter II-1 Part B (IMO, 2014) and the accompanied explanatory notes (IMO, 2017). As a result of the simplifications, the value $s_i$ is not an exact calculation of the probability of survival, and, therefore, neither is index A. However, $s_i$ and index A are still useful comparative measures and, therefore, they will be used as representations of the (total) probability of survival of the ship.

For the calculation of index A from the values of $p_i$ and $s_i$, the ship is considered in three loading conditions. The deepest subdivision draught ($d_s$) is the waterline which corresponds to the Summer Load Line draught of the ship. The light service draught ($d_l$) is the service draught corresponding to the lightest anticipated loading and associated tankage, including such ballast as may be necessary for stability and/or immersion. The partial subdivision draught ($d_p$) is the light service draught plus 60% of the difference between the light service draught and the deepest subdivision draught. For each loading condition a partial index can be calculated ($A_s$, $A_p$ and $A_l$) with the properties of the damage cases $p_i$ and $s_i$ that are relevant for that loading condition according to Eq. (1). The total index A consists of the three partial indices corresponding with the three loading conditions as shown in Eq. (2).

$$A = \sum_i p_i * s_i \tag{1}$$

$$A = 0.4A_s + 0.4A_p + 0.2A_l \tag{2}$$

Subsequently, the index A has to be higher than the prescribed index R. If the length of a cargo ship ($L_S$) is over 100 m, the index R is defined according to Eq. (3). If the length of a cargo ship is less than 100 m but greater than 80 m, the index R is defined according to Eq. (4). If a cargo ship is shorter than 80 m, there is no requirement concerning its subdivision index.

$$R = R_0 = 1 - \frac{128}{L_S + 152} \tag{3}$$

$$R = 1 - \frac{1}{1 + \frac{L_S}{100} * \frac{R_0}{1 - R_0}} \tag{4}$$

The index R described above is applicable to all cargo ships of 80 m in length and upwards. For passenger ships a separate index R is defined, which includes the number of persons the ship is allowed to carry. Cargo ships can only be excluded from this regulation if they comply with damage stability regulations of other instruments, of which a list is presented in SOLAS (IMO, 2014). Examples of these instruments are MARPOL, the International Bulk Chemical Code and the International Gas Carrier Code. However, the instruments that can be used as an alternative to SOLAS do not apply to the ships used in this study.

Concluding the explanation of the calculations, the index A is a property of the ship and it will remain a property of unmanned ships. If the index R of the ship is allowed to be lower, index A can also be lowered. Consequently, the layout of the ship might need less subdivision in compartments, which results in reduced building cost and more design freedom. Another option is that the ship may be allowed to sail with lower initial stability requirements, since these requirements are often limited by the need to comply with the index R. For the ships used in Section 4 of this article, it has been verified with the original designers that this indeed is the case. Sailing with lower initial stability increases the transport capacity of the ship, which increases the potential earnings of the ship.

### 2.2. Defining a risk profile

In order to be able to use equivalent safety for the assessment of the index R, 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). In other words, for something to be safe, it must be established what the acceptable level of risk is. Therefore, the assumption that the safety of autonomous ships should be equivalent to the safety of conventional ships means that both should be subjected to the same level of risk. For this study, the damage stability-related level of risk per accident of a conventional ship will be the benchmark for an unmanned autonomous ship of the same type and size.

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

The consequences of the event can be of different natures. For instance, the loss of human lives cannot directly be compared to the loss of a financial asset such as cargo. However, in this study concepts like the value of preventing a fatality (VPF) are used such that all consequences are expressed in monetary values.

To find the damage stability-related level of risk per accident of a ship, a number of steps have to be taken. The following description is a summary of these steps. Hereafter each step will be explained in more detail.

1) Define a list of possible damage cases.
2) Define the most important categories of consequences and how to calculate their costs.
3) Determine which damage cases lead to each of the categories of consequences.
4) Per category, multiply the probability of occurrence with the associated costs.
5) Sum the categories together.

The first step consists of making a list of the damage cases that can occur when the ship is damaged. This list is created using the procedure as described by IMO (IMO, 2017). As described in Section 2.1, for each damage case a probability of occurrence and a probability of survival can be calculated as well.

For the second step, the following categories are taken as the possible consequences of a damaged ship:

- Loss of cargo
- Loss of fuel
- Damaged machinery
- Steel damage
- Loss of life
- Total ship loss

The loss of cargo, loss of fuel, damaged machinery and steel damage are considered for the situation where the ship remains afloat. If the damage leads to a total ship loss, all these consequences are incorporated in the consequences of a total ship loss. The environmental impact is accounted for in the category loss of fuel and total ship loss in the form of clean-up costs. The determination of the values of the consequences is described in Section 3.

In the third step, the damage cases are linked to the consequences. Logically, all damage cases that a ship will not be able to survive will lead to the consequences of a total ship loss. All damage cases that the ship will be able to survive will have steel damage as a consequence. All damage cases that will penetrate a fuel tank (while the ship stays afloat) will have loss of fuel as a consequence. The latter also holds for loss of cargo and damaged machinery, but with the penetration of respectively a cargo hold and the engine room instead of a fuel tank.

Step two will provide the cost per category, while step three will provide the probability that a category will occur. In step four the probability of occurrence is multiplied with the associated cost to find the risk per category.

In step five the damage stability-related overall level of risk per accident is found by a summation of the risk per category.

### 2.3. Revision of the subdivision index

The steps described in Section 2.2 provide a method to establish the risk profile of a manned ship. The level of risk of the same ship, but without a crew, will be lower, since the risk of losing life is eliminated. Within the procedure to find the allowable reduction of index R, the overall level of risk of the unmanned ship will be changed such that it will become equivalent to the level of risk of the manned ship. Within this research, index A is changed for the unmanned ship until the total risk is equal to that of the manned ship.

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

As described in Section 2.2, the risk is calculated for six categories, which together form the overall level of risk. In Table 1 an overview is presented of each category that contributes to the overall level of risk for both a manned and an unmanned ship. In this overview the risk of each category is broken down into the cost of the consequence $C$ and the probability of occurrence. In the simplification it will be assumed that the costs of the consequences per category will not change for the unmanned ship.

The determination of the probability of occurrence differs per category. Steel damage occurs only when the ship stays afloat, thus with a probability of $A_m$. A total ship loss occurs with a probability of $(1 - A_m)$. The determination of the risk of loss of life is described in Section 3.5. The probabilities $q_{cargo}$, $q_{fuel}$ and $q_{machinery}$ are a combination of the factors $p$ and $s$ for the relevant damage cases of that category. Thus, $q$ represents the probability that the relevant sections of the ship are damaged, while the ship remains afloat.

From Table 1 it can be derived how the overall level of risk of a manned ship ($Risk_m$) and the overall level of risk of an unmanned ship ($Risk_u$) can be calculated. This can be done by multiplying the cost and probability per category and subsequently sum these categories.

Of all the components in Table 1 only four are unknown. These unknown components are those associated with the probability of occurrence for the unmanned ship. As mentioned before, the index A of the unmanned ship ($A_u$) will be found that would assure that the overall level of risk of the unmanned ship will be the same as the overall level of risk of the manned ship. However, if the index A is changed, the values of $q_{cargo,u}$, $q_{fuel,u}$ and $q_{machinery,u}$ will change too with respect to the manned ship.

The direct link between changes in the value of $A$ and changes in the values of $q_{cargo}$, $q_{fuel}$ and $q_{machinery}$ is unknown. However, it can be assumed that if the probability that the ship will survive changes (i.e. $A_u \neq A_m$), the probabilities of these categories also change. Within this procedure it will be assumed that the changes in the values of $q_{cargo}$, $q_{fuel}$ and $q_{machinery}$ will be proportional to the change in the index A from $A_m$ to $A_u$.

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

**Table 1**
An overview of the costs of consequence and probabilities of each category that contributes to the overall level of risk for both a manned and an unmanned ship.

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

## 3. Determination of consequences

As was mentioned before, the consequences for a damaged ship depend on the damage case that occurs. For any damage case, if the ship remains afloat, the consequences are a combination of one or more of the following categories: loss of cargo, loss of fuel, damaged machinery and steel damage. If the ship sinks, these consequences will occur as well and they are incorporated in the costs of a total ship loss. The loss of life is evaluated separately.

### 3.1. Loss of cargo

The loss of cargo will occur when a cargo hold is penetrated and the ship remains afloat. In the approach, it is conservatively assumed that all cargo in and above a penetrated cargo hold is lost. Especially for containerised cargo this is an overestimation, since the containers above deck do not necessarily have to be damaged if the cargo hold is damaged. However, as will be described in Section 4.2, the probability that the ship will stay afloat when a cargo hold is penetrated is very low, especially for small ships with only one cargo hold. The assumption is, therefore, considered acceptable.

Different types of cargos lead to different cargo values. E.g. containers are much more valuable than dry bulk. 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 average value (€40,000 (IHS Markit, 2017)) and maximum weight (24 tonnes) of a TEU would lead to a minimum value of around €1,600 per tonne.

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

### 3.2. Loss of fuel

If a fuel tank is penetrated, the fuel will flow out and that constitutes a threat to the environment. The fuel would need to be cleaned up, which incurs costs. The costs of cleaning up fuel are estimated at €37,819*$V^{0.7233}$ with $V$ the size of the spill equal to the volume of the penetrated tanks (IMO, 2018b). The value of the fuel that is lost is much lower than the clean-up costs and is incorporated in the uncertainty of the actual value of the clean-up costs. As will be discussed in Section 4.2, the sensitivity of the result to the loss of fuel is low. Therefore a more accurate estimation is not needed. If the damage case will cause the ship to sink, the clean-up costs are incorporated in the costs of a total ship loss.

### 3.3. Damaged machinery

When the engine room is penetrated while the ship remains afloat, the machinery will be damaged. The cost estimation of the damaged machinery is conservatively based on the costs of a new drive train. Aalbers provides a cost estimation for the entire drive train of €4,200*$P^{0.79}$, with $P$ the installed power (Aalbers, n.d.). As will be discussed in Section 4.2, the total risk's sensitivity to damaged machinery is low, even for this conservative calculation. Therefore a more accurate estimation of the costs of damaged machinery is not needed and 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.

### 3.4. Steel damage

After a collision where the ship remains afloat, 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 the 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 newbuilding price.

Next to the costs of dry-docking, the costs of repairs are estimated per meter of damage. 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. If only the outer hull is damaged, it is assumed that this corresponds to 1/8 of the cross-section. If the inner hull is damaged too, it is assumed that this corresponds to 1/4 of the cross-section. 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 costs of the repairs per meter of damage are calculated according to Eq. (5).

$$Cost_{repairs} = €14,500 * \frac{steelweight}{shiplength} * \left(\frac{1}{8} or \frac{1}{4}\right) \quad (5)$$

The total costs of steel damage per damage case is the costs of the dry-dock plus the costs of the repairs of the damage.

### 3.5. Loss of life

Crew members that are present on a ship that is involved in a collision are subjected to the potential of losing 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 of the probability of loss of life. According to EMSA, the VPF is approximately €6.25 million per fatality (European Maritime Safety Agency, 2015a). The risk of losing life is calculated by multiplying the probability of loss of life with the VPF.

In order to find the probability of loss of life during a collision, data on ship accidents from 2000 to 2012 is used (Eliopoulou et al., 2016). The data by Eliopoulou et al. is a collection and overview of the data available on collisions and fatalities. From this data the statistical average loss of life per accident (SALL) can be derived for general cargo ships, bulk carriers and containerships. The SALL is determined by dividing the number of fatalities by the number of accidents (see Table 2).

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

| | | General Cargo | Bulk carrier | Containership |
|---|---|---|---|---|
| Fleet at risk | | 118,325 | 67,822 | 45,099 |
| Collision accidents | Per shipyear | 5.75E-03 | 5.60E-03 | 7.20E-03 |
| | Total | 680 | 380 | 325 |
| Fatalities during collision | Per shipyear | 1.78E-03 | 1.92E-04 | 8.87E-05 |
| | Total | 211 | 13 | 4 |
| Statistical average loss of life | | 0.310 | 0.034 | 0.012 |

As can be seen in Table 2, the SALL differs strongly per ship type. This might be explained by the different average size of each ship type. Bulk carriers and containerships are generally much larger than general cargo ships, thus providing a safer environment for the crew in case of a collision. General cargo ships are generally small .to medium sized ships, while bulk carriers and container ships are more often medium to very large sized ships (Equasis, 2012). As will be described in Section 4.1, the effect of removing crew on the total level of risk is expected to be largest for smaller ships. Therefore, the accident data of general cargo ships is used in this analysis.

In the data by Eliopoulou et al. (2016) there is no distinction between fatalities when the ship was lost or stayed afloat. The lack of data on this subject makes it impossible to determine the cause of the fatalities during collision at this point. The SALL in Table 2 has been calculated with the assumption that fatalities occur evenly over all accidents. However, if the fatalities would only occur when the ship is lost, this would have an impact on the analysis. The other extreme is when the fatalities only occur when the ship is not lost. In Table 3 the SALL for the three interpretations of the data is presented for general cargo ships. The impact of these interpretations on the result will be evaluated in Section 4.4.

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

Concluding, the risk of losing life is calculated by multiplying the SALL with the VPF. The VPF is taken as €6.25 million and the SALL as 0.310, corresponding to the accident data of general cargo ships where the fatalities occur evenly over all accidents.

### 3.6. Total ship loss

The risk associated with a total ship loss is calculated by multiplying the probability of a total ship loss (1 minus index A) with the costs of a total ship loss. The costs of a total ship loss largely overlap the possible consequences if the ship remains afloat. They are represented by loss of cargo, loss of ship and wreck removal costs (including clean-up of any fuel spill). A risk of losing life is also present when the ship will be lost. However, the risk of losing life is determined independent of the survival of the ship, as described in Section 3.5.

**Table 3**
The statistical average loss of life for general cargo ships when the data is interpreted in three different ways.

| | Fatalities occur evenly | Fatalities occur when ship is lost | Fatalities occur when ship is not lost |
|---|---|---|---|
| Fatalities | 211 | 211 | 211 |
| Ship accidents considered | 680 | 77 | 603 |
| Statistical average loss of life | 0.310 | 2.739 | 0.350 |
| Probability of occurrence of accidents | 1 | 1 – A | A |

The value of the cargo on board of the ship will be lost and the calculations are the same as in Section 3.1. Also, evidently, the ship is lost and the ship has a certain value. It is assumed that ships are depreciated linearly over their entire lifetime towards their scrap value of a minimum of €190 per tonne of lightweight (Jain, 2017). It is assumed that on average ships are lost halfway through their expected lifetime.

The wreck will have to be removed and cleaning of the environment will be necessary in order to prevent damage to the environment. The costs related to these activities are highly dependent on the circumstances of the accident. However, EMSA provides an estimate of one to three times the newbuilding price of the ship (European Maritime Safety Agency, 2015b). In this research, two times the newbuilding price is taken as costs for wreck removal.

### 3.7. Overview

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

## 4. Explorative quantification

In this section, three ships will be analyzed. Ship 1 is assessed in detail, while ships 2 and 3 are used to demonstrate the impact of ship size. In Section 4.1 the three ships are presented. Next, in Section 4.2, the current, manned, risk profile of ship 1 is presented and the sensitivity of this result to changes in the data is discussed. In Section 4.3 the subdivision index that will ensure equivalent safety when the ship is unmanned is calculated. Subsequently, the results of the assessment associated with uncertainties in the accident data, as discussed in Section 3.5., are presented in Section 4.4. In Section 4.5 the results of the analysis of ship 2 and 3 are given and the differences between the three ships are discussed. Last, the possible benefits of a reduced required subdivision index are discussed in Section 4.6.

### 4.1. The ships

It is expected that the changes in the requirements concerning damage stability are largest for smaller ships. When the ship becomes larger, the size of the crew increases at a lower rate than the total value of cargo and of the ship. Therefore, it is expected that the contribution of the crew to the overall level of risk is lower for larger ships than for smaller ships.

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

| | |
|---|---|
| Loss of cargo | Based on number of TEU's lost<br>Cargo value: €40,000 per TEU |
| Loss of fuel | Based on volume of spilled fuel ($V$) in tonnes<br>Clean-up costs: €37,819*$V^{0.7233}$ |
| Damaged machinery | Based on costs of drive-train<br>Value: $\in 4,200 * (installedpowerinkW)^{0.79}$ |
| Steel damage | Consists of a constant part (docking) and a variable part (repairs)<br>Docking costs: 3% of newbuilding price<br>Repair costs per meter damage:<br>$€14,500 * \frac{steelweight}{shiplength} * \frac{1}{8} * type$ |
| Loss of life | Total risk of losing life: €1,939,000 regardless of the ship |
| Total ship loss | Cargo value: €40,000 per TEU carried<br>Value of ship: halfway its depreciation<br>Wreck removal: 200% of newbuilding price |

The method that is described in Section 2 will be used to assess the actual designs of three ships of increasing size, kindly provided by DEKC Maritime[2]. All the particulars that are needed to determine the consequences of any damage case are presented in Table 5.

Ship 1 is a general cargo ship with only one cargo hold. The engine room is located in the aft part of the ship. The ship has three fuel tanks, of which one is located next to the engine room on portside. The other two are located in the double hull in the middle of the ship. A rough overview of the layout of ship 1 can be found in Fig. 1.

Ship 2 is a concept design of a general cargo ship with two cargo holds. A consequence of being a concept design is that it is designed with a margin in the index A. The engine room is located in the aft part of the ship. The ship has four fuel tanks, two at each side of the aft cargo hold. A rough overview of the layout of ship 2 can be found in Fig. 2.

Ship 3 is a container feeder with three cargo holds. The ship has been designed before 2009 and therefor falls under old damage stability regulations. Although the old regulations are very similar to the new regulations, the consequence of using the old regulations is that the index A of ship 3 is lower than the (present) index R for a ship of this size. Also, for ship 3, a probabilistic damage stability assessment is not done for the partial loading condition, since that was not required for the old regulations. The engine room is located in the aft part of the ship. The ship has four fuel tanks, located in the space between the cargo holds. A rough overview if ship 3 can be found in Fig. 3.

### 4.2. Risk profile of manned ship 1

The assessment of ship 1 leads to the risk profile of the ship as presented in Table 6. The profile shows that following a collision, this ship has a 55.5% chance of sinking and a 45.5% chance of staying afloat. If the ship stays afloat, there is a 16.1% chance of penetrating a fuel tank, 4.1% chance of penetrating the engine room and 0.0% chance of penetrating a cargo hold when there is cargo inside. This last number is a result of the fact that ship 1 only has one cargo hold. If there is cargo present in this cargo hold and the cargo hold is penetrated, the ship will not be able to survive the damage. Therefore, the risk of losing cargo without losing the ship is equal to €0.

From the overview in Table 6 it can be seen that risk of a total ship loss is the main contributor to the damage stability-related overall level of risk. The risk of losing life also has a significant contribution. The remaining four categories, however, have a contribution of 1% or less. This results in an overall level of risk per accident of approximately €15.9 million.

Ship 1 is categorized as a general cargo ship, which means that it is designed to be able to transport different kinds of cargo. As has been mentioned in Section 3.1, the value of the cargo will depend greatly on the cargo the ship will carry. Since the probability of losing cargo, while

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

**Table 5**
The particulars of the ships that are evaluated in this article.

| | | Ship 1 | Ship 2 | Ship 3 |
|---|---|---|---|---|
| Ship type | | General cargo | General cargo | Container feeder |
| Length | [m] | 89.9 | 107.4 | 152.4 |
| Lightweight | [t] | 1503 | 1900 | 5174 |
| Steel weight | [t] | 1020 | 1200 | 3828 |
| Deadweight tonnage | [t] | 4050 | 6000 | 13,030 |
| TEU | [-] | 218 | 300 | 1036 |
| Crew | [-] | 10 | 8 | 18 |
| Installed power | [kW] | 1500 | 2500 | 9000 |
| Fuel oil | [t] | 308 | 220 | 1192 |
| Newbuilding price | [€] | 7 million | 10 million | 15 million |
| Required subdivision index | [-] | 0.444 | 0.507 | 0.579 |
| Attained subdivision index | [-] | 0.445 | 0.569 | 0.520 |

the ship remains afloat, is zero for this ship, the value of the cargo will not influence the category loss of cargo. However, the value of the cargo will have an influence on the cost associated with a total ship loss. If ship 1 would mainly be transporting commodities with a low value, such as grain, the overall level of risk is reduced with €3.7 million. This increases the contribution of the risk of losing life to the overall level of risk per accident and, therefore, this would increase the impact of removing the crew.

### *4.3. Revised subdivision index for ship 1*

Using the approach described in Section 2.3, the risk profile of an unmanned autonomous ship of the same type and size as ship 1 is found. The results are presented in Table 7. As can be seen, the risk of total ship loss increases, since the probability of losing the ship increases when index A is reduced. The overall level of risk per accident is mainly determined by the risk of a total ship loss. The unmanned autonomous ship should have an index A of 0.362 to be subjected to the same level of risk as the manned ship. This is a reduction of 0.083 or 18.7%.

Therefore, if the index R for the unmanned autonomous ship would be 0.362, it will be ensured that it will have equivalent safety compared to the manned ship.

### *4.4. Uncertainties in accident data*

As described in Section 3.5, uncertainties are present in the accident data and thus the risk of losing life, since it is not known how the loss of life relates to the sinking of the ship or the size of the ship. In Table 8 the resulting new index A of the unmanned autonomous ship is presented if the approach described in this article is used with different values for the risk of losing life. The results in Table 7 correspond to the results in the column 'general cargo ship – fatalities occur evenly' of Table 8.

The results in Table 8 show that the allowable change in the index varies significantly, depending on the cause of the fatalities. If it would be assumed that lives are only lost when the ship is lost, the risk of

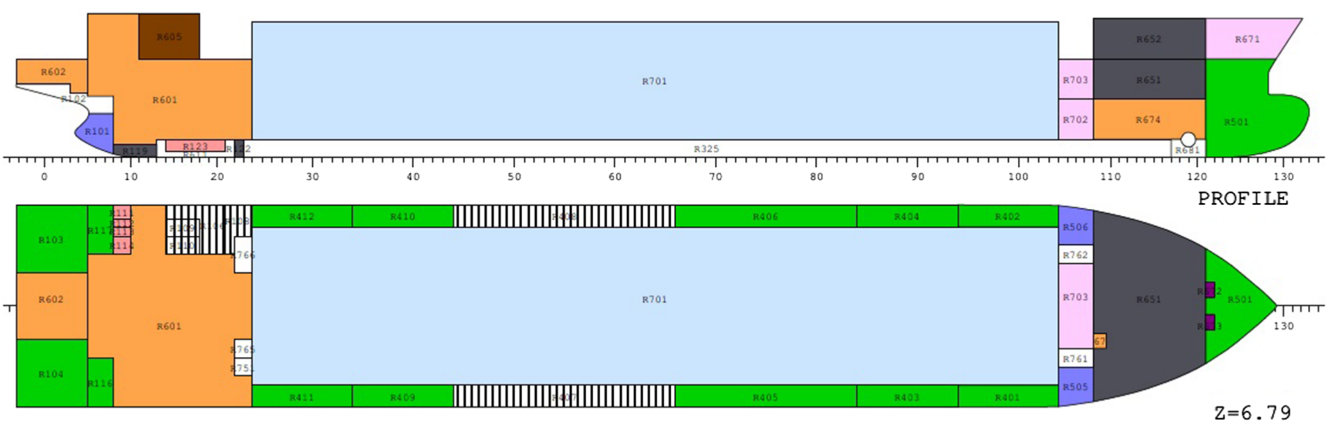


**Fig. 1.** Layout of ship 1, including a side view and a top view. The scale along the length of the ship represents the frames, with a spacing distance of 0.7 m between frames 24 and 104 and 0.6 m for the remaining frames. The blue area is the cargo hold. The orange area is the engine room. The black-striped areas are fuel tanks. The green areas are ballast tanks. The function of the remaining spaces is not relevant for this research. This figure has been provided by DEKC Maritime.

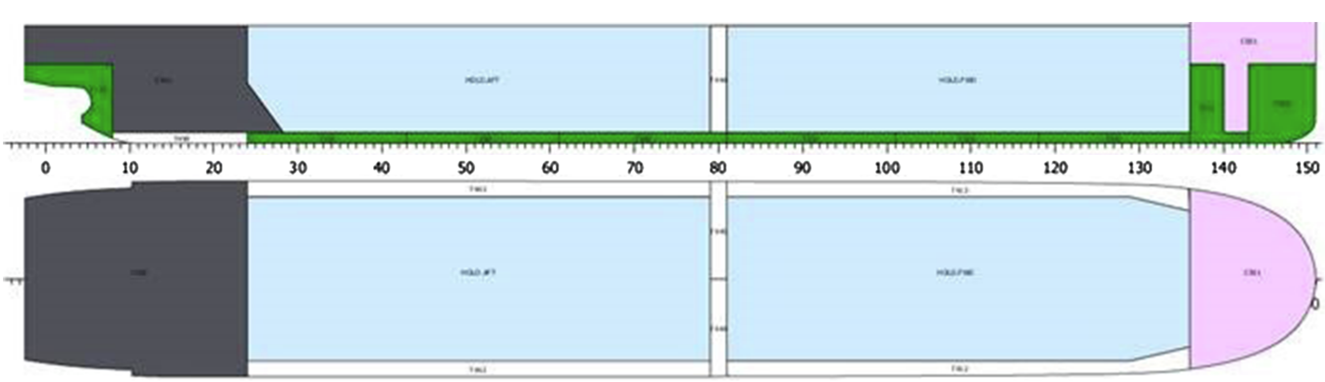


**Fig. 2.** Layout of ship 2, including a side view and a top view. The scale along the length of the ship represents the frames, with a spacing distance of 0.7 m. The blue areas are the cargo holds. The grey area is the engine room. The pink area is service space. The white areas are void space. The green areas are ballast tanks. This figure has been provided by DEKC Maritime.

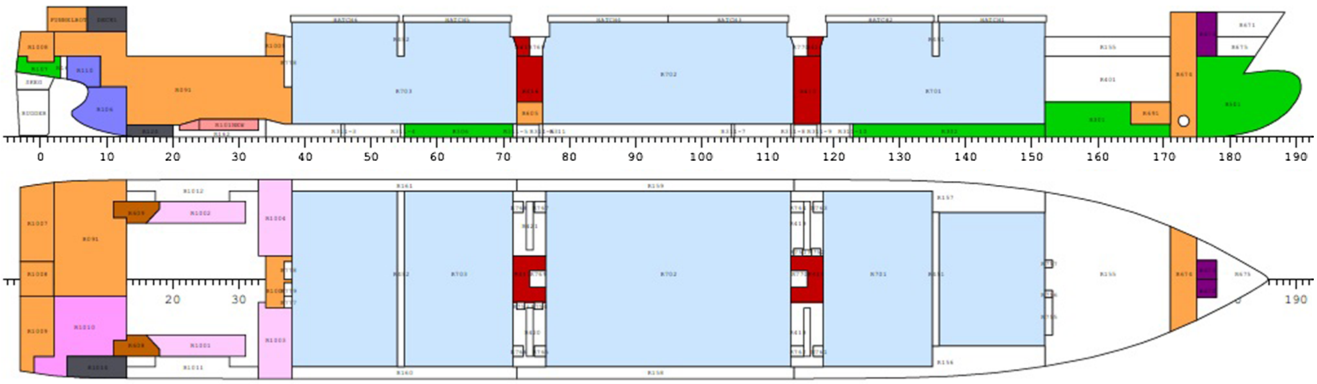

**Fig. 3.** Layout of ship 3, with a side view and a top view. The scale along the length of the ship represents the frames, with a spacing distance of 0.78 m. The blue areas are the cargo holds. The orange area in the stern is the engine room. The red areas are fuel tanks. The green areas are ballast tanks. The function of the remaining spaces is not relevant for this research. This figure has been provided by DEKC Maritime.

**Table 6**
Overview of the risk profile of ship 1 in its conventional form as a manned ship.

| Type | Risk | Probability | Contribution to the overall level of risk |
|---|---|---|---|
| Loss of cargo | € - | 0 | 0.0% |
| Loss of fuel | € 174,000 | 0.161 | 1.1% |
| Damaged machinery | € 56,000 | 0.041 | 0.4% |
| Steel damage | € 206,000 | 0.445 | 1.3% |
| Loss of life | € 1,939,000 | 0.310 | 12.2% |
| Total ship loss | € 13,478,000 | 0.555 | 85.0% |
| Overall level of risk per accident | € 15,854,000 | | |
| Attained subdivision index | | 0.445 | |

**Table 7**
Overview of the risk profile of ship 1 in its revised form as an unmanned ship.

| Type | Risk | Probability | Contribution to the overall level of risk |
|---|---|---|---|
| Loss of cargo | € - | 0 | 0.0% |
| Loss of fuel | € 142,000 | 0.131 | 0.9% |
| Damaged machinery | € 45,000 | 0.033 | 0.3% |
| Steel damage | € 167,000 | 0.362 | 1.1% |
| Loss of life | € - | – | – |
| Total ship loss | € 15,499,000 | 0.638 | 97.7% |
| Overall level of risk per accident | € 15,854,000 | | |
| Attained subdivision index | | 0.362 | |

losing life increases with a factor 5. Subsequently, the effect of removing crew is increased significantly. An index A of only 0.038 would suffice to ensure that the ship will have equivalent safety compared to the manned ship.

If it would be assumed that fatalities only occur when the ship will stay afloat, the effect of removing crew on the reduction of index A decreases. Although in that case the average loss of life per accident increases slightly, the risk of losing life is only present on the 44.5% of the ships that are expected to stay afloat. As a result, the risk of losing life is half of the original. Subsequently the effect of removing crew is also halved.

The results also show that the differences in SALL per ship type have a significant effect on the outcome. In Table 8 the result of the analysis is shown, if ship 1 would have been evaluated as if it is a containership. Although this will not change anything to the ship, it will have an effect on the statistical average loss of life. The accident data shows that the statistical average loss of life linked to a collision on a containership is only 0.012, which is a factor 26 lower than the statistical average loss of life linked to general cargo ships. As a result, the risk of losing life is also a factor 26 lower and the effect of removing crew becomes negligible. The difference between containerships and general cargo ships might be explained by the fact that containerships are generally larger than general cargo ships. As was mentioned in Section 3.5, general cargo ships are generally small to medium sized ships, while bulk carriers and container ships are more often medium to very large sized ships (Equasis, 2012). On larger ships the crew is less likely to be close to the location of impact. Also, the probability of survival is bigger for larger ships, which makes the consequences of the impact less severe.

The uncertainties described in this section show that further research is needed in order to find a more substantiated value for the risk of loss of life. These recommendations are described in Section 6.

### *4.5. Analyses of ship 2 and 3*

Ships 2 and 3, as presented in Section 4.1, have been evaluated with the same approach as ship 1 in Sections 4.2 and 4.3. The results for ship 2 and 3 are summarized in Table 9 and Table 10 respectively. As was mentioned in Section 4.1, it was expected that the impact of removing crew would be lower for larger ships. The results in this section confirm this expectation.

**Table 8**
The allowable changes in required subdivision index for different interpretations of the accident data. The results under general cargo ship use different assumptions for the cause of fatalities. The result under containership assumes that fatalities occur evenly over all accidents.

| | General cargo ship | | | Containership |
|---|---|---|---|---|
| | Fatalities occur evenly | Fatalities occur when ship is lost | Fatalities occur when ship is not lost | Fatalities occur evenly |
| SALL | 0.310 | 2.739 | 0.350 | 0.012 |
| Risk of losing life | € 1,939,000 | € 9,505,000 | € 973,000 | €77,000 |
| $A_{new}$ | 0.362 | 0.038 | 0.404 | 0.442 |
| Change | −0.083 | −0.407 | −0.041 | −0.003 |
| % | −18.7% | −91.5% | −9.4% | −0.7% |

**Table 9**
Overview of the risk profile of ship 2 in both its conventional form as a manned ship and its revised form as an unmanned ship.

| | Manned ship | | Unmanned ship | |
|---|---|---|---|---|
| Type | Risk | Probability | Risk | Probability |
| Loss of cargo | € 654,000 | 0.109 | € 585,000 | 0.097 |
| Loss of fuel | € 120,000 | 0.155 | € 107,000 | 0.139 |
| Damaged machinery | € 317,000 | 0.156 | ‘ 284,000 | 0.140 |
| Steel damage | € 466,000 | 0.574 | € 417,000 | 0.513 |
| Loss of life | € 1,939,000 | 0.310 | € - | – |
| Total ship loss | € 14,835,000 | 0.426 | € 16,938,000 | 0.487 |
| Overall level of risk | € 18,331,000 | | € 18,331,000 | |
| Attained subdivision index | | 0.574 | | 0.513 |

**Table 10**
Overview of the risk profile of ship 3 in both its conventional form as a manned ship and its revised form as an unmanned ship.

| | Manned ship | | Unmanned ship | |
|---|---|---|---|---|
| Type | Risk | Probability | Risk | Probability |
| Loss of cargo | € 73,000 | 0.005 | € 69,000 | 0.005 |
| Loss of fuel | € 60,000 | 0.026 | € 57,000 | 0.024 |
| Damaged machinery | € 256,000 | 0.046 | € 242,000 | 0.043 |
| Steel damage | € 904,000 | 0.520 | € 855,000 | 0.492 |
| Loss of life | € 1,939,000 | 0.310 | € - | – |
| Total ship loss | € 34,164,000 | 0.480 | € 36,173,000 | 0.502 |
| Overall level of risk | € 37,396,000 | | € 37,396,000 | |
| Attained subdivision index | | 0.520 | | 0.492 |

For both ships it can be seen that a reduction in the required subdivision index can be allowed while ensuring equivalent safety. For ship 2 a reduction in the attained subdivision index of 0.061 or 10.5% results in equivalent safety. For ship 3 a reduction in the attained subdivision index of 0.028 or 5.4% results in equivalent safety.

A comparison of these three ships should be performed with care, because of some fundamental differences. The most important difference is that ship 1 has an index A that is almost equal to its index R, while the index A of ship 2 is too high and the index A of ship 3 is too low. However, despite these differences the effect of these differences will not influence the general conclusion that the allowable reduction will be larger for smaller ships.

For a more substantiated conclusion more ships will need to be analysed, such that the influence of the differences of each ship can be determined. However, this will be more useful if a better estimate of the risk of losing life is available. The uncertainties as described in Section 4.4 have a larger impact on the result of the analysis, than the differences between the ships.

### 4.6. Possible benefits of a reduced required subdivision index

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

An evaluation of ship 2 showed that for an allowable decrease in the index A of 0.10, it can be expected that the number of tanks in the ship can be reduced significantly, as has been confirmed with the designers of the relevant ships. Tanks are often subdivided into smaller tanks (e.g. into a port side, starboard and double bottom tank) to limit their impact on intact stability through free surface effects and their impact on damage stability in case they are penetrated. Reducing the number of tanks will decrease the steel weight of the ship, the number of pumps and valves needed and the total length of piping in the ship. Also, it is expected that the man-hours needed for construction will decrease as well as the work for the engineer. In total, it is expected that these effects will result in a reduction in the newbuilding price of the ship by several percent.

Another option is to lower the minimum value of stability indicator GM that the ship is allowed to sail with. For most ships, the minimum value of GM is limited in order to attain the required subdivision index. For the ships used in this article it has been verified with the original designers that this is the case. By reducing this limit, the ship will be able to carry more cargo. The extra cargo a ship will be able to carry will depend on the ship and the cargo specifications. For the specific case of a fully loaded ship 1 this means that it will be able to increase its capacity by 5%. This increase has been estimated by using a lightship weight of 1503 tonnes with a centre of gravity of 5.93 m above the keel. In the fully loaded conditions, the fuel tanks will be completely filled. The ship will be initially loaded with 180 containers, each of them weighing a standard 14 tonnes. A surplus of 1300 tonnes of ballast water will be needed to realise the original minimum value of GM of 0.50 m. Reducing the attained subdivision index of ship 1 from 0.445 to 0.362 allows the ship to sail with a minimum value of GM of 0.30 m. As a result, the ship will be able to carry 9 extra containers on the top layer.

## 5. Conclusions

The assessment of a 4,050 ton deadweight ship shows that the risks associated with a total ship loss and loss of life are the main contributors to the damage stability-related level of risk. Therefore, removing the crew reduces the overall level of risk significantly for autonomous ships of this size. An assessment of a 6,000 ton deadweight ship and a 13,030 ton deadweight ship shows that the impact decreases when the ships become larger.

Subsequently, based on equivalent safety, the required subdivision index can be lowered for unmanned autonomous ships. However, the allowed reduction decreases when the ships become larger. Moreover, as can be seen in the results, the size of the reduction depends strongly on missing accident statistics concerning the loss of life. Further research to reduce these uncertainties is described in the recommendations.

Even small reductions of the required subdivision index might already lead to an increase in transport capacity by reducing the minimum initial stability the ship is allowed to sail with, which is especially important for container ships. For larger reductions in the required subdivision index this effect can be extended by a simpler and more efficient design.

## 6. Recommendations

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

Furthermore, the relation between the size of the crew and the risk of losing life is unknown. It is recommended to investigate if the casualties occurred randomly over all accidents, regardless of the size of the crew, or if the risk of losing life is associated with the risk of losing the entire crew. Additionally, this investigation should indicate whether more lives are lost on ships that stay afloat or ships that sink after a collision.

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

There seems to be a discrepancy between the probability of survival as used by IMO and the probability of survival that can be derived from accident data. The probability of survival as defined by IMO, or the attained subdivision index, is lower than 0.7 for ships under 275 m and thus for most ships. Therefore, according to the attained subdivision index at least 30% of the accidents concerning collision should lead to a total ship loss. From accident data it can be derived that only 11% or less of the accidents concerning seagoing cargo ships lead to a total ship loss, depending on the type of ship. It is acknowledged that assumptions are used in the prediction of the survivability of a ship, which make the prediction deviate from reality. However, it is recommended to perform a case study to further improve the predicted survivability of ships in collision accidents.

## 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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