Assessment of the Required Subdivision Index for autonomous ships based on equivalent safety

de Vos, Jiri; Hekkenberg, Robert

Publication date
2019

Document Version
Final published version

Published in
Proceedings of the International Seminar on Safety and Security of Autonomous Vessels (ISSAV) and European STAMP Workshop and Conference (ESWC) 2019

Citation (APA)
de Vos, J., & Hekkenberg, R. (2019). Assessment of the Required Subdivision Index for autonomous ships based on equivalent safety. In O. A. Valdez Banda, P. Kujala, S. Hirdaris, & S. Basnet (Eds.), *Proceedings of the International Seminar on Safety and Security of Autonomous Vessels (ISSAV) and European STAMP Workshop and Conference (ESWC) 2019* (pp. 14-23). Sciendo.

International Seminar on Safety and Security of Autonomous Vessels
17 - 18 September 2019, Helsinki

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

Jiri de Vos[1,*], Robert Hekkenberg[1]
[1] Department of Ship Design, Production & Operation, Delft University of Technology, the Netherlands

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. However, to achieve the required design freedom, the existing regulatory framework will have to be amended. 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 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. The index gives a requirement for the allowed probability of sinking when a ship is damaged due to collision or contact. The safety level is related to the safety of ship, cargo, environment and crew. 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. If the principle of equivalent safety is applied, a lower subdivision index can be accepted for unmanned autonomous vessels. In this article, the level of risk that a manned ship is subjected to will be derived by means of a risk analysis. In this risk analysis all logical consequences of a collision will be taken into account, covering both the probability of losing the entire ship and the consequences of the cases where the ship will not sink. Thereafter, the Required Subdivision Index for unmanned ships, which ensures an equivalent safety level to an equivalent manned ship, is established. The sensitivity of the result to changes in the data is discussed as well.

Keywords: Required Subdivision Index; SOLAS; Autonomous Ships; Risk Analysis; Equivalent Safety

1. INTRODUCTION

The research effort on autonomous ships has increased over the last years. The realisation of an autonomous ship will have as a consequence that the crew can be reduced significantly or even be removed entirely. Nevertheless, the business case of autonomous ships is still hard to make. As for most innovations within the maritime industry, the incentive for autonomous ships is economic efficiency (Karlis, 2018). 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 the change to autonomous shipping would have on transport costs (Frijters, 2017; Rødseth & 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 of shipping, under the assumption that the probability that an incident occurs does not change, since the lives of the crew are no longer at risk. If the risk is lower, the requirements to the design of unmanned ships

---

[*] Corresponding author: phone, +31626737843, and email address, jiridevos@gmail.com

might become less strict, while maintaining equivalent safety. In this way more design freedom can be realised for unmanned ships and thus more economic efficiency.

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

Other regulatory instances such as DNV GL and Bureau Veritas already shared their belief in the need for a new regulatory framework for autonomous ships. The development of a new regulatory framework would be the next step for IMO following the RSE. The regulatory instances have described what they believe the new regulatory framework should look like, but the proposals remain of a qualitative nature. There is only limited research being performed on defining the new regulations for autonomous ships.

The new regulations should ensure that autonomous ships will be as safe as manned ships. However, as stated before, this could lead to changes in the requirements that will create more design freedom for autonomous ships.

Within this article the required subdivision index will be evaluated and it is assessed how this index could be lowered, while still maintaining equivalent safety in case the ship is completely unmanned. In this article an approach is used to find the allowable reduction of the index for single ships.

In section 2 the method of the assessment is described. The basis of the method is derived from safety science, which will be elaborated upon first. The general approach is described as well. Next the concept of probabilistic damage stability and how this is used in the approach is explained. Thereafter, the determination of the consequences of damage is discussed. Last, the example ship that will be assessed is presented. In section 3 the results of the assessment are presented along with a discussion on these results. In section 4 the conclusions are presented. The recommendations follow in section 5.

2. METHOD

2.1. On equivalent safety

In order to be able to use equivalent safety for the assessment of the required subdivision index, 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 subject to the same level of risk. For this study, the damage stability-related level of risk of a conventional ship will be the benchmark for an unmanned autonomous ship of the same type and size.

Risk is defined as “a measure of the likelihood that an undesirable event will occur together with a measure of the resulting consequence within a specified time” (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 that an event will not happen and that an event will definitely happen respectively.

The consequences of the event can be of a different nature. For instance, the loss of human lives cannot directly be compared to the loss of a financial asset such as cargo. However, concepts such as the value of preventing a fatality (VPF) are used such that all consequences are expressed in monetary values. 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 damages where the ship remains afloat. If the damage leads to a total shiploss, these categories are incorporated in the consequences of a total shiploss. The determination of the values of the consequences is done is section 2.3.

Concluding, in order to find the damage stability-related level of risk, the following steps have to be taken. If it is known that the ship is damaged, the events that have to be evaluated are the damage cases that can occur. Each damage case has a probability of occurrence and a probability of survival. The determination of the damage cases and the probabilities is described in section 2.2. It can be determined which damage cases lead to each of the categories of consequences. For each category, the risk per damage case is determined by multiplying the probability of occurrence with the consequences of that category. The total risk per category is the summation of the risk of that category per damage case. The overall damage stability-related level of risk is the summation of the risk per category.

For the transition towards an unmanned autonomous ship, the overall level of risk is reduced with the risk of loss of life, when it is assumed that the design remains unchanged. Since this lowers the overall level of risk, changes to the unmanned autonomous ship can be allowed. The changes should result in a change of the probability of occurrence for the remaining categories of consequences. This is further described at the end of section 2.2. The costs of the consequences are assumed to remain unchanged.

2.2. Probabilistic damage stability

The requirement concerning damage stability is called the required subdivision index (referred to as index R). The attained subdivision index of a ship (referred to as index A) has to be higher than index R. The definitions of index R and A are described in SOLAS (IMO, 1980).

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

A damage case is a situation where one or more adjacent compartments are flooded. The length of the damage of a certain damage case corresponds to the overall length of the compartments under consideration. The height of the damage corresponds to the height of the bulkhead deck. The depth of the damage corresponds to the minimum depth of the compartments under consideration. The probability of occurrence of the damage cases is derived from a study by Lützen on ship collisions (Lützen, 2001). SOLAS prescribes a method to calculate the probability of occurrence for the specific damage case (p_i).

The flooding of the compartments has an influence on the stability of the ship. The new stability properties are used to calculate a probability of survival for the specific damage case (s_i). Together with the probability of occurrence, this number is used to calculate index A.

$$A = \sum_i p_i * s_i$$

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. The total index A consist of three partial indices (A_s, A_p and A_l) corresponding with the three loading conditions as follows:

$$A = 0.4A_s + 0.4A_p + 0.2A_l$$

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

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

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

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

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

The method of finding the probability of occurrence and the probability of survival for the damage cases is used in the risk analysis as described in section 2.1. A lower index R for a ship of a certain type and size gives the possibility to reduce the index A. If the index A changes, the probability of occurrence and the probability of survival of the damage cases also change. Subsequently the overall level of risk of the ship also changes.

Within the approach that is described in this article, it will be assumed that all probabilities will change with the same rate. The rate is defined as $\frac{A_u}{A_m}$, where A_m is the index A of the manned ship under consideration and A_u is the index of the unmanned autonomous ship, of the same type and size, that results in the same level of risk. By using a solver the value of A_u can be found. The differences between A_m and A_u is the allowable change in the index R for the considered ship of a certain type and size.

Small reductions of the index A can be realised by reducing the minimum GM the ship is allowed to sail with or by reducing the number of tanks in the ship. These changes can already lead to more transport efficiency. Even more transport efficiency can be realised if larger reductions of the index A are allowed.

2.3. 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.

2.3.1 Loss of cargo

The loss of cargo will occur when a cargo hold is penetrated and the ship remains afloat. The loss of cargo when the ship is lost is incorporated in the consequences of a total shiploss. The risk of losing cargo is calculated by establishing the damage cases that lead to the penetration of a cargo hold, while the ship remains afloat. The risk per damage case is the probability that the damage case occurs multiplied with the costs of the loss of cargo. The total risk of losing cargo is a summation of the risk of all the relevant damage cases.

The worst case scenario is evaluated, where it is assumed that all cargo in and above a penetrated cargo hold is considered to be lost. Different types of cargos lead to different cargo values. E.g. containers are much more valuable than dry bulk. The most transported dry bulk by ship are coal, iron ore and grain, accounting for nearly two thirds of the dry bulk trade (Chen, 2017). Of these three commodities the most valuable is grain. Its current value is €185 per tonne, which is about three times higher than the value of coal and iron ore ("Wheat vs Coal," 2019; "Wheat vs Iron Ore," 2019). The average value (€40,000 (IHS Markit, 2017)) and 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. The value per TEU will be taken as €40,000 (IHS Markit, 2017). In partial loading conditions, 60% of the capacity of each cargo hold is used.

2.3.2 Loss of fuel

If a fuel tank is penetrated, the fuel will flow out and that would be a threat to the environment. The fuel would need to be cleaned up, which will include costs. The risk of losing fuel is calculated by establishing the damage cases that lead to the penetration of a fuel tank, while the ship remains afloat. The risk per damage case is the probability that the damage case occurs multiplied by the costs of the loss of fuel. The total risk of losing fuel is a summation of the risk of all the relevant damage cases.

The costs of losing fuel are estimated using the size of the spill by $€37{,}819 * V^{0.7233}$ (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 3, 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.

2.3.3 Damaged machinery

When the engine room is penetrated, while the ship remains afloat, the machinery will be damaged. The risk of damaged machinery is calculated by establishing the damage cases that lead to the penetration of the engine room, while the ship remains afloat. The risk per damage case is the probability that the damage case occurs multiplied by the costs of damaged machinery. The total risk of damaged machinery is a summation of the risk of all the relevant damage cases.

The cost estimation of the damaged machinery is 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 3, the sensitivity of the result to damaged machinery is low. 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.

2.3.4 Steel damage

After a collision where the ship remains afloat, the damages 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. Per damage case the risk of steel damage is calculated by multiplying the probability of the damage case with the relevant costs of the repairs. The total risk of steel damage is a summation of the risk of all the relevant damage cases.

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, 2013), the costs of the repairs per meter of damage are calculated as follows:

$$Cost_{repairs} = €14{,}500 * \frac{steel\ weight}{ship\ length} * \left(\frac{1}{8}\ or\ \frac{1}{4}\right)$$

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.

2.3.5 Loss of life

Crew members that are present on a ship that is part of a collision are subjected to the potential of losing life. The loss of life can be compared with other risks by using the VPF. The VPF is a value that represents society’s willingness to pay for small reductions of the probability of losing life. According to EMSA, the VPF is approximately €6.25 million per fatality (European Maritime Safety Agency, 2015b). The risk of losing life is calculated by multiplying the probability of losing life with the VPF.

In order to find the probability of losing life during a collision or contact, data on ship accidents from 2000 to 2012 is used (Eleftheria, Apostolos, & Markos, 2016). The data by Eleftheria 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 1).

As can be seen in Table 1, the SALL differs 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 (Equasis, 2012), thus providing a safer environment for the crew in case of a collision. As will be described in section 2.4, 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.

Table 1: Finding the statistical average loss of life during collision or contact for general cargo ships, bulk carriers and containerships.

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

In the data by Eleftheria 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 or contact at this point. The SALL in Table 1 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 2 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 3.

Table 2: The SALL for general cargo ships when the data is interpreted in three different ways.

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

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 0.252, corresponding to the accident data of general cargo ships where the fatalities occur evenly over all accidents.

2.3.6 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 resemble the possible consequences if the ship remains afloat, but are represented by loss of cargo, loss of ship and wreck removal costs (including clean-up of any fuel spill). The costs related to the potential loss of life are incorporated in the category “loss of life”.

The value of the cargo on board of the ship will be lost and the calculations are the same as in section 2.3.1. Also, evidently, the ship is lost and the ship has a certain value as well. It is assumed that ships are depreciated over their entire lifetime towards their scrap value of a minimum of €190 per LDT (Jain, 2017). Since this is a study on the potential of losing the ship, it is assumed that on average ships are lost halfway their expected lifetime. Therefore, the value of the ship is taken as halfway its depreciation.

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, 2015a). In this research, two times the newbuilding price will be taken as costs for wreck removal.

2.4. The ship

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 does increases with a lower rate compared to the amount of cargo, installed power or capital costs. 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.

The method that is described in the previous paragraphs will be used to assess a 4,000 ton deadweight general cargo ship. All the particulars that are needed to determine the consequences of any damage case are presented in Table 3. The ship has 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.

Table 3: The particulars of the ship that is evaluated in this article.

Ship type	General cargo
Length	89.9 m
Lightweight	1503 t
Steel weight	1020 t
DWT	4050 t
TEU	218
Crew	10
Installed power	1500 kW
Fuel oil	308 t
Newbuilding price	€7 million
Required subdivision index	0.444
Attained subdivision index	0.445

3. RESULTS AND DISCUSSION

The assessment of the ship described in section 2.4 leads to the risk profile of the ship as presented in Table 4. From this overview 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. Thus even if these categories are underestimated with a factor two, the risk profile of the ship changes only little. The risk of losing cargo is even zero. The reason is that this ship has only one cargo hold. If the cargo hold is penetrated, the probability of survival is always zero. The contribution of the loss of cargo related to a total shiploss, however, is significant and will increase with the size of the ship. A more accurate estimation of the costs of loss of fuel, damaged machinery and steel damage is not required.

Table 4: Overview of the risk profile of the ship under evaluation 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	€ 1,577,000	0.252	10.2%
Total ship loss	€ 13,479,000	0.555	87.0%
Overall level of risk	€ 15,491,000		
Attained subdivision index		0.445	

Using the approach described in this article, the risk profile of an unmanned autonomous ship of the same type and size is found. The results are presented in Table 5. As can be seen, the risk of total ship loss increases, since the probability on losing the ship increases when index A is reduced. The overall level of risk is mainly determined by the risk of a total ship loss. The unmanned autonomous ship should have an index A of 0.378 to be subjected to the same level of risk as the manned ship. This is a reduction of 0.067 or 15.2%.

Therefore, if the index R for the unmanned autonomous ship would be 0.378, it will be ensured that it will have equivalent safety compared to the manned ship.

Table 5: Overview of the risk profile of the ship under evaluation 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	€ 148,000	0.137	1.0%
Damaged machinery	€ 47,000	0.035	0.3%
Steel damage	€ 175,000	0.378	1.1%
Loss of life	€ -	-	-
Total ship loss	€ 15,122,000	0.622	97.6%
Overall level of risk	€ 15,491,000		
Attained subdivision index		0.378	

As described in section 2.3.5, uncertainties are present in the accident data and thus the risk of losing life. In Table 6 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 5 correspond to the results in the column ‘general cargo ship – fatalities occur evenly’ of Table 6.

The results in Table 6 show that the allowable change in the index varies significantly, depending on the cause of the fatalities. The results also show that the differences per ship type have a significant effect on the outcome. Therefore, further research to reduce the uncertainties is needed and are described in section 5.

Table 6: 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	0.252	2.720	0.278	0.009
Risk of losing life	€ 1,577,000	€ 9,428,000	€ 774,000	€59,000
A_{new}	0.378	0.041	0.412	0.443
Change	-0.067	-0.404	-0.033	-0.002
%	-15.2%	-90.8%	-7.5%	-0.6%

4. CONCLUSIONS

The assessment of the 4,000 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.

Subsequently, based on equivalent safety, the required subdivision index can be lowered for unmanned autonomous ships. However, 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 GM the ship is allowed to sail with. For larger reductions in the required subdivision index this effect can be extended by a simpler and more efficient design.

5. RECOMMENDATIONS

There seems to be a discrepancy between the theoretical probability of survival and the probability of survival that can be derived from accident data. The theoretical probability of survival of a ship is equal to the attained subdivision index, which is lower than 0.7 for ships under 275 metres and thus for most ships. Therefore, it is expected that at least 30% of the accidents concerning collision or contact should lead to a total ship loss. From accident data it can be derived that only 10% or less of the accidents concerning sea going cargo ships lead to a total ship loss, depending on the type of ship. It should be further investigated why the theory differs from the reality. Therefore it is recommended to perform a study on cases of collision and contact. Within this study it should be derived what the theoretical probability of survival was after the ship was damaged. This should indicate whether all ships that should have been lost in theory actually were lost and whether all ships that should have survived in theory actually survived.

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

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 incidentally 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.

This research focusses on the events and consequences that assume that a ship is damaged as a result of collision or contact. The probability that a ship is part of a collision or contact is not taken into account. It may well be that the probability that a ship is part of a collision will change if the transition towards unmanned ships is made. If this probability increases, a higher survivability of the ship might be required. 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.

ACKNOWLEDGEMENTS

The research leading to these results has been conducted within the NOVIMAR project (NOVel Iwt and MARitime transport concepts) and received funding from the European Union Horizon 2020 Pro-gram under grant agreement n° 723009. The design and data of the ship used in this research has been provided by DEKC Maritime. The authors would like to thank Herbert Koelman, Lector Maritime Innovative Technologies at Maritiem Instituut Willem Barentsz and director of SARC, for his support in the understanding of and working with probabilistic damage stability.

REFERENCES

Aalbers, A. (n.d.). Evaluation of ship design options.

Butler, D. (2013). *A Guide to Ship Repair Estimates in Man-hours*. Elsevier. https://doi.org/10.1016/C2011-0-07776-1

Chen, J. (2017). Dry Bulk Commodity. Retrieved May 6, 2019, from https://www.investopedia.com/terms/d/dry-bulk-commodity.asp

Eleftheria, E., Apostolos, P., & Markos, V. (2016). Statistical analysis of ship accidents and review of safety level. *Safety Science*, *85*, 282–292. https://doi.org/10.1016/j.ssci.2016.02.001

Equasis. (2012). The World Merchant Fleet in 2012.

European Maritime Safety Agency. (2015a). *Impact assessment compilation part 1; Impact assessment in accordance with the EC IA*.

European Maritime Safety Agency. (2015b). *Risk Acceptance Criteria and Risk Based Damage Stability. Final Report, part 1: Risk Acceptance Criteria*.

Frijters, T. (2017). *Future Ships*. TU Delft.

Hansen, K. F. S. (2013). *Analysis of estimations, quotations and actual costs related to dry-docking*.

IHS Markit. (2017). *Vessel Accumulation and Cargo Value Estimation*.

IMO. (1980). *International Convention for the Safety of Life at Sea (SOLAS), 1974 as amended*. IMO.

IMO. (2013). *Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments*. *MSC.1/Circ.1455*. IMO.

IMO. (2018a). *Regulatory Scoping Exercise for the Use of Maritime Autonomous Surface Ships (MASS)*.

IMO. (2018b). *Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process*. *MSC-MEPC.2/Circ.12/Rev.2*. IMO.

Jain, K. P. (2017). *Improving the Competitiveness of Green Ship Recycling*. Delft University of Technology.

Karlis, T. (2018). Maritime law issues related to the operation of unmanned autonomous cargo ships. *WMU Journal of Maritime Affairs*, *17*(1), 119–128. https://doi.org/10.1007/s13437-018-0135-6

Lützen, M. (2001). *Ship Collision Damage*. *Technical University of Denmark*. https://doi.org/10.1111/j.1365-2958.2006.05502.x

Papanikolaou, A., & Eliopoulou, E. (2008). On the development of the new harmonised damage stability regulations for dry cargo and passenger ships. *Reliability Engineering and System Safety*, *93*(9), 1305–1316. https://doi.org/10.1016/j.ress.2007.07.009

Rødseth, Ø., & Burmeister, H.-C. (2015). D10.2: New Ship Designs for Autonomous Vessels, (First outline).

Wheat vs Coal, South African export price - Price Rate of Change Comparison. (2019). Retrieved May 6, 2019, from https://www.indexmundi.com/commodities/?commodity=wheat&commodity=coal-south-african

Wheat vs Iron Ore - Price Rate of Change Comparison. (2019). Retrieved May 6, 2019, from https://www.indexmundi.com/commodities/?commodity=wheat&commodity=iron-ore