Real-time onboard flooding risk assessment for passenger ships for ship-to-ship collisions

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ABSTRACT

Software for real-time estimation of flooding risk onboard passenger ships (or ships in general) should be capable of identifying a potential hazard and evaluating a risk level associated with the detected danger. The present work presents a framework for real-time risk assessment in case of potential ship-to-ship collisions. As real-time risk assessment pertains to both phases before and after an accident, the present work focuses on the risk of flooding before an accident occurs. More precisely, the paper describes the step necessary to develop a database-based software for real-time risk assessment during navigation, focusing on the detection and likelihood of possible ship-to-ship collisions potentially dangerous for the ship. As such, the tool should be capable to identify a hazard, evaluating the risk level associated with the hazard and advise the crew of potential risks. The software should work in symbiosis with onboard instrumentation, receiving data from, for example, Radar, GPS and AIS in real-time. Given these inputs, the software should calculate the route of potential striking ships, estimating the possible future collision. Afterwards, in case of possible collisions, the software interrogates a damage surrogate model derived from a database of direct crash simulations, providing in real time a set of potential breaches. Such breaches are then associated with a time to capsize, derived from a survivability surrogate model derived from a set of time-domain flooding simulations. Then it is possible to evaluate risk as the Potential Loss of Life (PLL) in real time. Such an approach is fully based on direct first-principles calculations and compliant with the multi-level framework developed in project FLARE for flooding risk.

Keywords: *Flooding risk, onboard risk evaluation, Passenger ships, damage stability, evacuation.*

1. INTRODUCTION

The survivability assessment of a passenger ship after a flooding event has been always identified with the analysis and judgment of the residual righting lever curve (Rahola, 1939). The approach intrinsically requires the definition of a “sufficient” amount of stability to be compared with the vessels’ righting arm for several conditions. However, the meaning of the required “safety” threshold is still not well defined by in-force regulations (IMO, 2009), considering the Required Index R as an acceptance/rejection instrument. The effective meaning of the goal of keeping the vessel upright and afloat has been first discussed in the early 2000s by applying the Risk-Based Design (Papanikolaou, 2009) to the “Design for Safety” of passenger ships. This, in turn, corresponds to ensuring the design of a vessel with a known safety level, which, in case of damage stability, corresponds to a known flooding risk (Vassalos 2009, 2012). The evaluation of such a risk requires the availability of suitable instruments for the understanding of survivability as a function of time (Vassalos et al. 2022a) and advanced analyses to evaluate the evacuation time in case of a flooding casualty (Guarin et al. 2014).

Risk analysis for passenger ships does not cover only the design phase but should also include the operational phase (Du et al. 2020) or the whole life cycle in general (Vassalos et al. 2022b). To this end, risk models for passenger ships should evaluate risk as a combination of susceptibility to an accident and vulnerability to an accident (Goerland and Montewka, 2015). This means estimating accident occurrence and its consequences, as is usual among industries (Aven, 2012). Recent approaches suggest abandoning a rigorous determination of probabilities in favour of a more in-depth analysis of accident uncertainties (Aven, 2022). Therefore, to reduce uncertainties, the use of first principle-based tools should be pursued for the evaluation of flooding risk.

In this sense, the application of dynamic flooding analysis for the determination of survivability (Mauro et al. 2022) together with the determination of direct crash simulations to determine the breach dimensions (Conti et al. 2022) may tackle the challenge of performing a real-time estimation of risk for onboard applications, employing the Possible Loss of Lives (PLL) as risk metrics (Vassalos et al. 2022c).

The present paper presents a new framework for the real-time risk assessment of passenger ships due to a possible ship-to-ship collision event. The framework employs a multi-level approach to risk allowing for different grades of approximations for the ship's survivability and for the consequences of a possible accident. A notional example highlights the feasibility of the proposed concept for real-time flooding risk assessment onboard passenger ships.

2. MULTI-LEVEL RISK ASSESSMENT

The risk due to flooding can be represented by the Possible Loss of Lives (PLL), which is compliant with the general definition of risk and is defined by the following equation:

$$PLL = p_f \cdot c_f \qquad (1)$$

where p_f is the probability of flooding and c_f is the consequence of the flooding event. Both probabilities and consequences can be estimated with different levels of accuracy, extending the findings initially elaborated for damage stability frameworks to risk assessment. This means employing a multi-level approach for the evaluation of *PLL*.

The multi-level approach allows for adopting different levels of confidence for the methods employed to determine the *PLL*. Considering a single possible scenario, equation (1) can be rewritten in the following form:

$$PLL = p \cdot (1-s) \cdot FR \cdot POB \qquad (2)$$

In equation (2) the occurrence is indicated by *p* and the survivability is expressed by *s*, commonly used for damage stability analyses, while the consequences are evaluated through the fatalities associated with the event, which means the people on board *POB* times the fatality rate *FR*.

The different values or probabilities related to the occurrence, survivability and fatality are associated with different levels in the risk evaluation process in a multi-level framework, as outlined in Figure 1. More precisely, the occurrence is determined by the preparation of the input and by a Level 1 survivability assessment. Level 1 or Level 2 damage stability calculations define survivability and evacuation handling determines the fatality.

Accordingly, the different levels correspond to different *PLL* levels as it is described in the following sub-sections.

PLL level 1

This approach employs only static damage stability calculations. As such, this method presents a high level of approximation on both survivability and fatalities determination. In fact, the expected number of fatalities depends on the time to capsize of the ship but static analysis does not account for time-dependent phenomena.

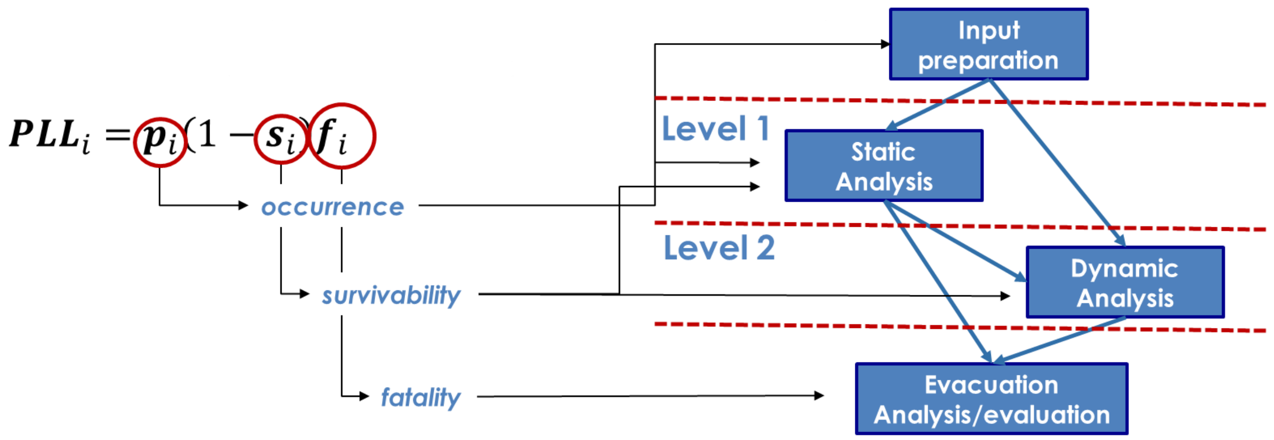

Figure 1: Multi-level framework for flooding risk.

As such, the fatality rate requires an approximated estimation at this stage. To keep the formulation as simple as possible, taking into account the dependencies between survivability and fatality rate, the following simplifying assumptions are made:

$$FR = \begin{cases} 0.8 & \text{if } s < 1 \\ 0.0 & \text{if } s = 0 \end{cases} \quad (3)$$

This simple and conservative approach aligns with the considerations and findings of the EU-founded project EMSA III. This assumption has been further supported by Project FLARE, stating that, considering time-domain flooding simulations, there is evidence that almost 80% of damage scenarios in a survivability assessment are transient capsizes (Paterson et al. 2021), which means conditions where no time for evacuation is available.

PLL level 2

The main parameters for a Level 2 flooding risk estimation are the time to capsize (*TTC*) and the time to evacuate (*TTE*). The *TTC* relates to identifying the time it takes the vessel to capsize/sink after a flooding event. Therefore, an accurate estimate of *TTC* requires the execution of time-domain flooding simulations, abandoning the static approach.

The *TTE* indicates the time needed for an orderly evacuation of passengers and crew onboard a passenger ship after a flooding hazard occurs. Hence, a proper determination of *TTE* requires the execution of advanced evacuation analyses in the time domain. However, the multi-level framework allows for a further simplification of the *FR* determination, allowing for the selection of two sub-levels for a Level 2 analysis.

The first sub-level of approximation, level 2.1, considers time-domain flooding simulations to determine *TTC*. *TTE* does not require evacuation simulations. Therefore, *FR* is determined in an approximate way as a function of TTC according to the following empirical formulations:

$$FR = \begin{cases} 0.0 & \text{if } TTC > n \\ 0.8\left(1 - \dfrac{TTC - n}{30 - n}\right) & \text{if } 30 \le TTC \le n \\ 0.8 & \text{if } TTC > 30 \end{cases} \quad (4)$$

where n is the maximum allowable evacuation time in seconds according to MSC.1/Circ. 1533. Therefore, the assumption of equation (4) intrinsically considers the nature of the capsize as a function of *TTC*, considering that is not possible to evacuate the ship in case of a fast transient capsize.

The second sub-level, level 2.2, implies a direct evaluation of the *TTE*. Starting from significant cases where the *TTC* determined through time-domain allows for starting a ship evacuation, motions and floodwater can be imposed to an evacuation software. Such a coupling allows for a direct comparison between the evacuation process and the associated *TTC*. Figure 2 reports the procedure to determine the fatality rate *FR* (*fr* in the picture), which is the result of the intersection between the evacuation curve and the mean time to capsize *TTC** among multiple repetitions of time-domain flooding simulations in irregular waves.

Thanks to this multi-level framework, the single definitions of probabilities and evaluation of survivability and fatalities can be obtained for different phases of the vessel life cycle. Thus, the methodology can be the starting point also for the definition of an application for real-time risk assessment.

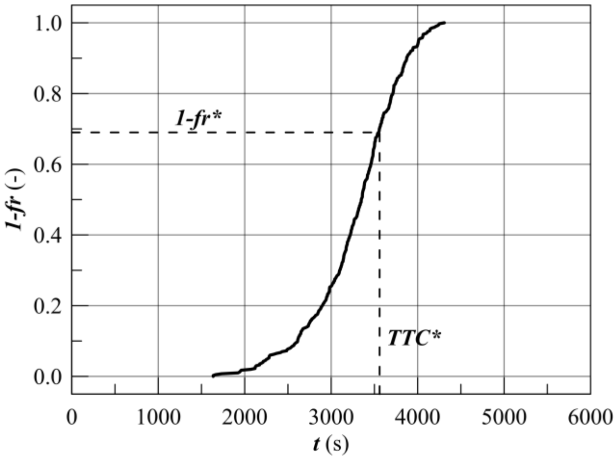

Figure 2: Fatality rate evaluation according to Level 2.2.

3. REAL-TIME RISK ASSESSMENT

The above-described framework for risk assessment is a starting point for the determination of a procedure for real-time risk assessment. Software for real-time risk estimation on-board of passenger ships (or ships in general) should be capable of performing the following tasks:

- Identify potential hazards
- Evaluate risk levels associated with the detected danger.
- (optional) Provide countermeasures to reduce risk.

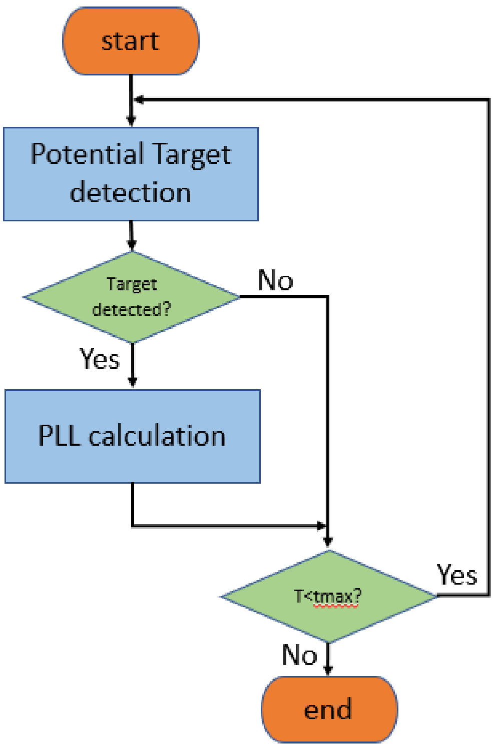

Figure 3: Flowchart of the steps needed for real-time PLL estimation during a voyage.

The last point is set as optional because it pertains to a DSS (Decision Support System), which is outside of the scope of the present work. The proposed approach is oriented to provide a preliminary guideline for the estimation of real-time risk during two phases:

- Before an accident.
- After an accident.

These two aspects require dedicated separate analyses and implementations However, the present work considers only the evaluation of real-time flooding risk before an accident occurs. The evaluation of the risk after an accident requires more insight into the evacuation analysis process.

Going back to the determination of risk assessment in real-time of a potential collision with another ship, the final outcome of the process should be an instantaneous estimation of the *PLL*. Then, the process should follow the steps reported in Figure 3.

As mentioned earlier, the estimation of *PLL* can be performed according to the multi-level framework for risk assessment. The aim is to use first principle-based tools, which means the process should ensure a level 2 estimation of *PLL*. As previous studies within the FLARE project show a minimal difference between level 2.1 and level 2.2 predictions, the real-time risk estimation is here covered up to level 2.1, thus neglecting evacuation analyses.

Figure 4 outlines how a real-time risk estimation tool has to be composed. The first step for an onboard risk assessment tool for ship-to-ship collisions is the detection of a potential hazard, using the data available from the onboard instrumentation (e.g. GPS, AIS, radar, etc...). Such an issue requires estimating the route, speed, and main dimensions of all potential striking ships within a certain distance. Besides, the environmental conditions should be defined from onboard instruments or weather data from local agencies/stations. Subsequently, there is the need to estimate the future path of the target ships, evaluating the most probable collision point, velocity, and encounter angle in case of collision detection. Such actions can be performed by employing different levels of simplifications. Estimation of the route can be performed by consecutive interrogations of GPS, Radar, or AIS data, evaluating the future position of an object based on its actual position, heading, and speed.

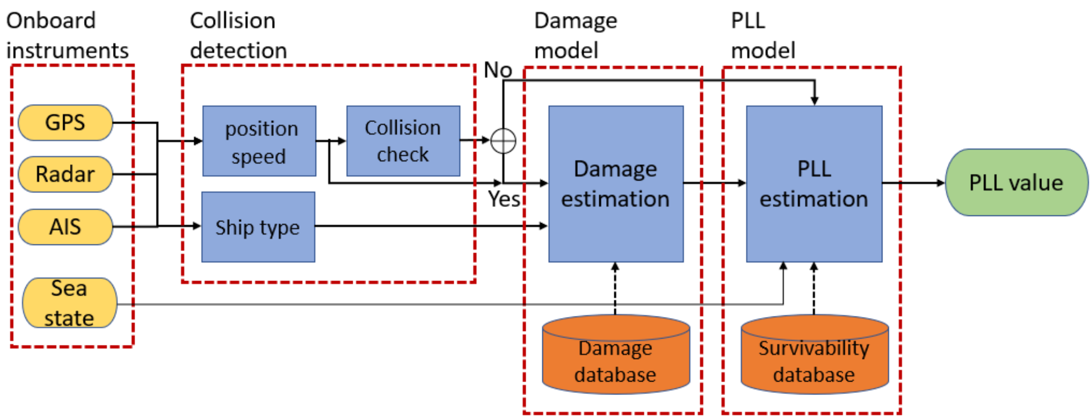

Figure 4: On-board real-time risk estimation outline before accident occurrence.

Table 1: Input needed for an onboard real-time flooding risk assessment.

Input name	unit	Instrumentation
Ship latitude	deg	GPS
Ship longitude	deg	GPS
Ship speed	kn	GPS or Speed mes.
Ship heading	deg	GPS or compass
Target latitude	deg	GPS, AIS, Radar
Target longitude	deg	GPS, AIS, Radar
Target speed	kn	GPS, AIS, onboard PC
Target heading	deg	GPS, AIS, Radar
Target ship type	-	AIS
Target ship length	m	AIS
Target ship breadth	m	AIS
Target ship draught	m	AIS
Significant wave height	m	Wave radar, motions, statistics

The possibility to have multiple sources for the input variables allows for the potential mitigation of loss of data, as, especially for AIS sources, the transmission may not be continuous (Montewka et al., 2021). Table 1 reports the list of inputs needed by the onboard tool together with the associated data source.

The data coming from instrumentation are subject to errors and uncertainties, which, for modelling, requires the knowledge of all the sensors and measuring systems involved in the collision detection tool. However, with this knowledge being unavailable within the FLARE project, a general Gaussian model is considered, sufficiently general to be further extended and modified in subsequent more detailed studies.

According to the adopted assumptions, the uncertainties assume the following form:

$$p(x_i) = \frac{1}{2\pi\sigma_i} e^{-\frac{1}{2}\left(\frac{x_i-\mu_i}{\sigma_i}\right)^2} \quad (5)$$

where μ_i is the signal provided by the instrumentation (interpreted as the mean of the Gaussian process) and σ_i is the standard deviation used to simulate uncertainties.

According to the scheme given in Figure 4, the input data with associated uncertainties enters a damage model, which estimates the dimensions of the breach associated with the collision event. As, due to uncertainties, the input is composed of distributions, the damage model provides output distributions of possible breaches. Subsequently, the breach distribution provides inputs to the survivability model, which evaluates the *PLL* in two steps. First, the *TTC* is evaluated through a surrogate model generated by a database of time-domain simulations referring to critical scenarios for the ship (Mauro et al. 2022). Afterwards, equation (5) is applied to each member of the *TTC* distribution, generating a *PLL* distribution. The real-time *PLL* value is then determined as a Quasi-Monte Carlo integration process on a sample of input values. Such an approach lead to the final calculation of *PLL* with the following formulation:

$$PLL \approx \frac{1}{N_{QMC}} \sum_{i=1}^{N_{QMC}} PLL_i\left(x_{D_i}, V_{T_i}, \beta_{T_i}\right) \quad (6)$$

Where x_D is the longitudinal position of the breach centre, V_T is the target ship speed and β_T is the collision angle. As the core of the process is the determination of the damage model and of the *PLL* model, it is worthy to further describe them in the next sections.

Damage model

The damage model for real-time risk assessment should be based on databases of direct calculations composed of outputs coming from crash analyses. To this end, different software can be employed but a valuable compromise can be given by the super element method, employing SHARP code, which gives results comparable with BEM analyses as tested in dedicated crash analyses benchmark (Kim et al., 2022).

This methodology is capable of providing an estimation of the breach's main dimensions (length L_D, penetration B_D, lower and upper vertical limits z_{LL} and z_{UP}) and the energy absorbed by the impact. The required inputs are the location of the impact x_D, the speed of the target ship V_T, the collision angle β_T and the side of the impact I_{side}. Having as input the outputs of the damage detection module, the SHARP calculation became a suitable method for generating a database of damages. Even though the calculation is quite fast compared to BEM analyses, the required calculation time remains high for a calculation in real-time.

Therefore, an alternative has to be found for the estimation of damage dimensions in real time. SHARP allows for performing a wide set of preliminary calculations that can be used to perform a bulk of initial crash analyses suitable for the generation of an initial database of potential damages. As such, the database gives a sufficiently accurate description of potential damages.

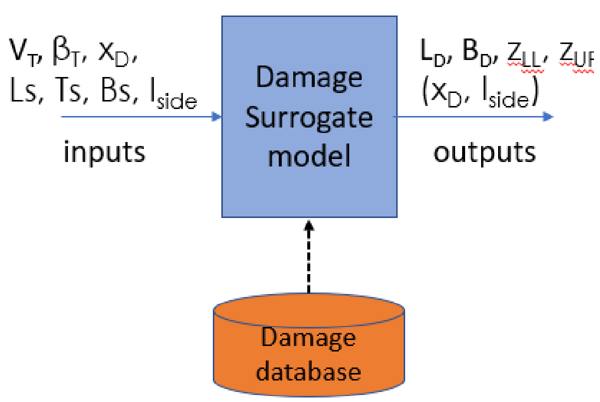

Figure 5: damage model schematisation with inputs and outputs.

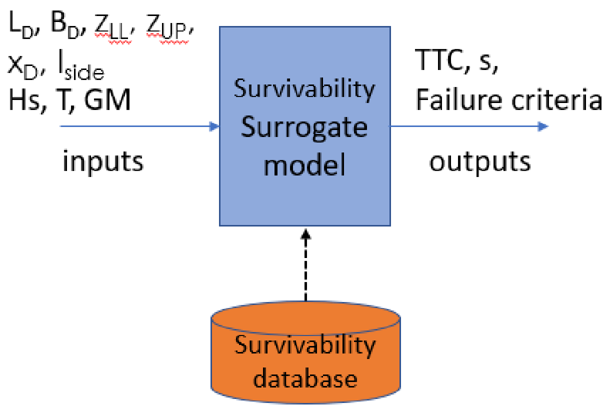

Figure 6: survivability model schematisation with inputs and outputs.

Besides the generation of the database itself, it is necessary to investigate also a method to generate a proper surrogate model from the database, suitable to provide all the relevant information concerning the breach faster than in real-time. Therefore, the general schematisation of the damage model can be the one shown in Figure 5.

From the collision detection model, the values and indicators that are provided to the damage model coincide with the input necessary to identify a SHARP simulation, i.e. the striking ship speed V_T, the relative heading β_T, the collision location x_D, the side identifier Iside and the striking ship main dimensions (*Ls*, *Bs* and *Ts*).

As the provided input to the damage model is subject to uncertainties, it is unlikely to consider such input values are unique and distinct. Therefore, the process considers a distribution of input values, more precisely a normal distribution for each input having the mean as provided by the collision detection model and the standard deviation reflecting the uncertainty of the process (in case it is possible to determine it) or more generally an ignorance factor. A detailed overview of the methodology is given by Mauro et al. (2023).

As a direct consequence, also the provided outputs will be subject to uncertainties and thus provided as distributions instead of single values.

PLL model

After the definition of the real-time damage characteristics through the damage model, the PLL should be evaluated. PLL determination is composed of three steps, as shown in equation (2), necessary to evaluate the case occurrence, the survivability and the fatality rate.

In a real-time risk assessment, the process is not properly the same, as the concept of occurrence is no longer related to the probabilistic distributions of the damages and environmental conditions described for the probabilistic approach to *PLL* calculation. The collision detection model determines the occurrence, which means that once the collision is predicted p is equal to 1, 0 otherwise. More precisely, the effective p is given by the distribution of values given by the collision model, thus it is inherited in the *PLL* model too. The *PLL* model can be then split into two sub-models, one for survivability and one for the fatality rate, to be applied in cascade.

The survivability model is schematised in Figure 6 concerning the surrogate model that should be applied here for the same reasons highlighted for the damage model. A direct method for survivability implies using dynamic simulations that are far away to be directly employed for real-time predictions. Also in this case a database of calculations should be created, taking into consideration the relevant inputs that may affect a dynamic flooding simulation.

A general description of the methods suitable for survivability surrogate model generation is provided in Vassalos et al. (2023).

4. DATABASES CALCULATION EXAMPLE

Hereafter, an example is given of the surrogate models generated from databases of flooding simulations and crash calculations. The test case refers to a cruise ship having the dimensions reported in Table 2. The reference ship is the principal reference hull of the FLARE project, being one of the hull forms used for benchmarking damage stability codes (Ruponen et al. 2022).

Table 2: Reference cruise ship main particulars.

Characteristic	symbol	value	Unit
Length between perpendiculars	L_{PP}	216.8	m
Breadth moulded	*B*	32.2	m
Depth	*D*	16.0	m
Design draught	*Ts*	7.2	m

Furthermore, this ship has been used as a reference for all the developments leading to the establishment of the design phase risk framework. Thus, it gives confidence in the accuracy of results coming out from PROTEUS3 flooding simulations and SHARP crash analyses.

The generation of surrogate models for real-time risk evaluations necessitates the definition of pertinent databases for damage dimensions and survivability. The proper definition of damage and survivability dataset requires the filling of a wide multi-variable space, leading to the execution of a significant number of simulations for either crash or dynamic analyses. The correct minimum number of simulations needed to capture all the possible scenarios has not been yet defined and should be studied in the future. Here, to provide an example of the process an arbitrary number of simulations has been selected, based on the experience with crash analyses and flooding simulations damage screening.

To generate the damage database, a set of scenarios has to be generated from a set of collision simulations between the reference ship and a set of potential striking vessels. Mauro et al. (2023) report the dimensions of the vessels employed as possible striking (target) ships for SHARP collision simulations. Those ships are a representative sample of the worldwide fleet. For this example 11 potential striking ships have been considered, simulating with the super element method 5500 possible scenarios, considering a combination of collision angles (uniformly distributed between 20 and 90 degrees), vessels speed (2,4,6,8,10 m/s), the longitudinal position of impact (uniformly distributed between 0.2 and 0.8 *L*) and 3 draughts for each vessel.

For the survivability database, it is necessary to evaluate the *TTC* from a set of flooding simulations with PROTEUS3 software. The strategy for creating the database is different from the conventional damage stability assessment according to SOLAS and FLARE design phase framework. Here, instead of performing damage screening on a set of 10,000 damages generated with statutory marginal distributions, a reduced set of 500 breaches is performed employing uniform distribution for the damage characteristics. Such an approach allows for detecting critical cases, giving uniform coverage of all possible breaches that may occur on the reference ship (Mauro et al., 2022).

Thanks to the employment of the QMC sampling method, the coverage of the breach space is in any case more evenly distributed than using conventional MC methods. Therefore, with 500 simulations it is possible to describe with sufficient accuracy the possible breaches that may occur after a collision. As the simulations deals also with irregular waves at the Hs of 1.0, 2.0, 3.0 and 4.0 metres, 10 repetitions per scenario have been carried out to consider the random phases in the wave spectrum. Therefore a total number of 20,500 simulations has been performed on the reference ship, evaluating the *TTC* per each damage case as the mean value among the 10 repetitions. The simulation time has been set to 90 minutes for all the simulated scenarios.

Figure 7 gives an overview of the results obtained from the crash analyses. The figure shows just a part of the data for the sake of brevity, as more detailed analyses require dedicated work and are not in the scope of the present paper and have been provided in Mauro et al. (2023). For damages, the dependency of damage penetration with the position is presented, considering all 11 striking ships (different colours), highlighting the uniformity of results across the length of the vessel.

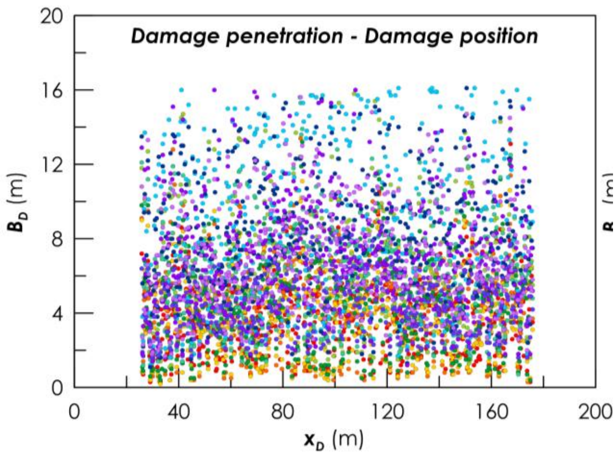

Figure 7: crash simulation results showing the dependence of damage penetration with the damage location.

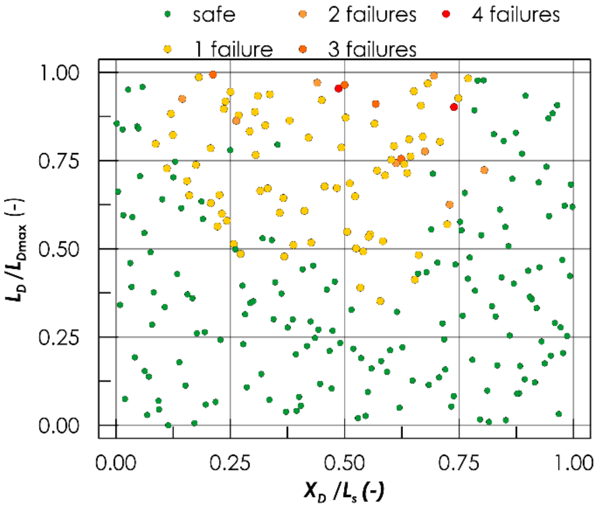

Figure 8: Flooding simulation results with critical damage identification.

Figure 8 shows the results of flooding simulations performed with PROTEUS3, highlighting the damages critical for ship survivability according to the failure criteria defined in Mauro et al. (2022).

The dependency of the damage length with the position is reported for the flooding simulations. For the calm water case, The different colours refer to the number of criteria that failed during the simulations, which means criteria related to the maximum heeling, the average heeling in a given time, and the amount of water entering the ship at the end of the simulations. Such criteria are the standard applied in dynamic flooding analyses. Also in this case it is possible to notice the uniform coverage of the space obtained by applying the QMC sampling. Therefore the two databases cover a possible design space for damages and associated vulnerabilities.

Having two homogeneous databases allows for determining surrogate models to quickly evaluate the damage dimensions and the *TTC*. Here, the models have been derived employing a multiple linear regression technique. For the damage dimensions the variables to be considered are 5, the striking vessel speed, the collision angle, the longitudinal position of damage, the striking vessel draught and the struck vessel draught. Employing a complete 4th-order polynomial regression (except for the two draughts that go up to the 2nd order), the final regression has been obtained removing not significant variables to maximise the goodness of fit of the regression.

Figure 9 shows the predicted/starting values for the damage length, penetration and upper/lower limitations. As reported in the figure, the obtained regressions have a high value for the goodness of fit, thus the model is a good representation of the initial database.

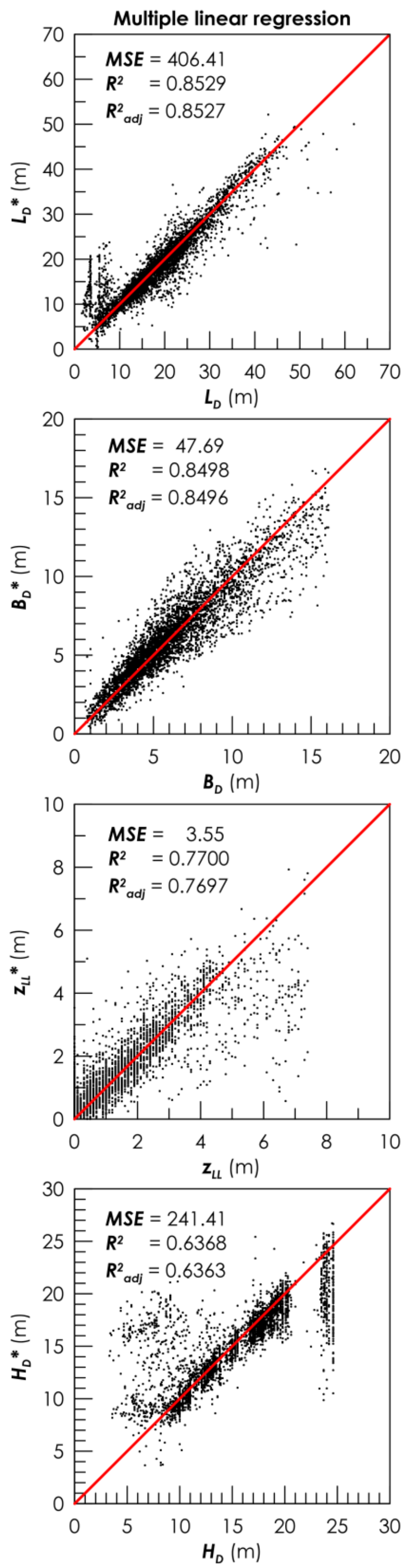

Figure 9: Surrogate models for damage dimensions on the reference ship.

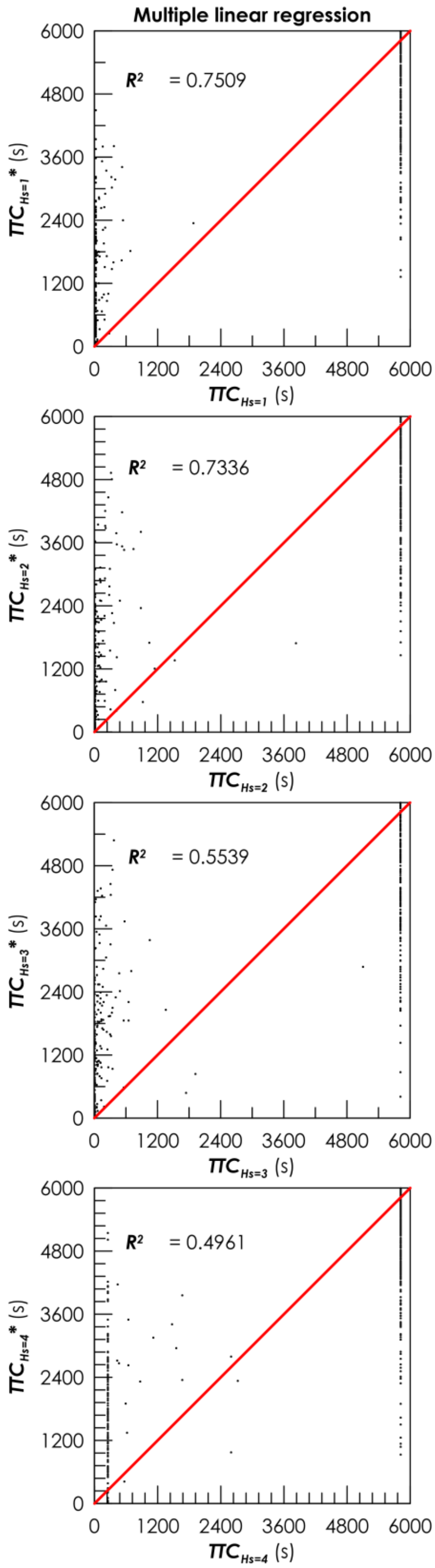

Figure 10: Surrogate models for survivability at *Hs*=1, 2, 3 and 4 metres.

The same has been performed for the TTC. In this case, the initial variables are the damage dimensions and location. However, the goodness of fit is not always giving a real effective matching between predicted and observed data. For this specific TTC case, this is important as a wrong prediction of the variable may lead to a wrong detection between capsize and not capsize of the ship in the same scenario. Figure 10 shows the predicted/starting values for *TTC* in the four irregular wave environments analysed in this example. It can be observed that the predicted and observed values are dense close to the extremities of the *TTC* space, having higher density closer to *TTC*=0 seconds. This happens for all the tested conditions but increasingly the significant wave height strengthens the phenomenon as *TTC* intrinsically reduces. This is a problem for the regression models, as it is hard to reproduce well the behaviour close to the extremities of the domain. Therefore, for *TTC*, the employment of more advanced regression techniques may be suggested.

Notwithstanding the above, the two surrogate models for damage dimension and *TTC* can be used to demonstrate the feasibility of the level 2.1 *PLL* calculation in real time for possible onboard applications.

5. FEASIBILITY FOR ONBOARD APPLICATION

Even though the above-mentioned databases are not yet available for a wide set of passenger ships, it is possible to test with the fictitious models presented afore the capability of the developed approach for the execution of real-time computations. To this end, the process has been implemented with the described surrogate models for breach location and dimensions and the *PLL*. Besides, gaussian errors have been added to the main input to simulate the uncertainties of the sensors producing the inputs to the models. Such a strategy allows for the testing of the calculation procedure and the evaluation of the suitability of a Quasi-Monte Carlo integration to evaluate the real-time *PLL*.

Therefore, the present test follows the subsequent steps for the simulation of a real-time calculation system:

- Generation of arbitrary input data from onboard sensors.
- Addition of Gaussian noise to simulate sensor uncertainties.
- Sample an amount N_{QMC} of breaches from the Gaussian input with a QMC method.
- Evaluate the distribution of the *PLL* at a level 2.1

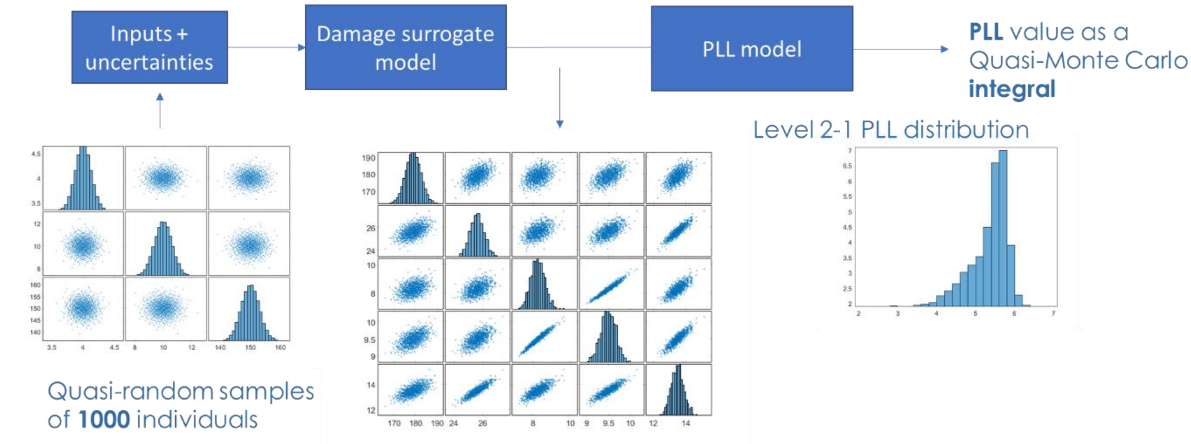

Figure 11: Real-time *PLL* calculation with uncertainties as a QMC process.

Proper modelling of errors and uncertainties requires the knowledge of all the sensors and measuring systems installed onboard and involved in the collision detection tool. Here, the Gaussian model presented in equation (5) is employed because of the lack of specific information on the onboard system's specifications.

In the demonstration, the value modelled with this uncertainty is the target ship speed V_T, the position of the breach centre x_D and the collision angle β_T. The arbitrary standard deviation reference values for the demonstration have been set to 1.5 knots for the speed, 10 metres for the breach position and 5 degrees for the angle. The value is arbitrary and should be not intended to be proposed as the real value to be used on an onboard tool, is just reference input used to test and demonstrate the applicability of the real-time *PLL* calculation.

Figure 11 shows the final process of calculation of real-time *PLL* including the uncertainties in the input values. The total calculation time necessary to estimate the *PLL* is of 0.03 seconds employing a polynomial model for the damages and *TTC*. Thus the process can be applied in real-time computations.

6. CONCLUSIONS

The present paper formalises the concept of real-time risk assessment onboard of passenger ship for the specific case of possible ship-to-ship collisions. The adoption of a multi-level framework established for the risk assessment of passenger ships during the design phase has been modified to accommodate the peculiarities of a real-time prediction. The resulting process allows for the evaluation of real-time risk employing as a metric the *PLL* at a level 2.1.

The work discusses the importance of the strategies and methodologies that should be employed to generate the databases and surrogate models for damage dimensions and survivability by using direct calculations as the primary source.

Finally, The application on a notional example allows for assessing the suitability of the proposed calculation methodology for onboard application in real-time. This conceptual study is the starting point for further investigation on the applicability of better surrogate models and the implementation of realistic errors for onboard instrumentation.

REFERENCES

Aven, T., 2012, "The risk concept -- historical and recent development trends," *Reliability Engineering & System Safety*, 99, p. 33-44.

Aven, T., 2022, "A risk science perspective on the discussion concerning Safety I, Safety II and Safety III", *Reliability Engineering & System Safety*, 217, p. 108077.

Conti, F., Le Sourne, H., Vassalos, D., Kujala, P., Lindroth, D., Kim, S., Hirdaris, S., 2022, "A comparative method for scaling solas collision damage distributions based on a ship crashworthiness application to probabilistic damage analysis of a passenger ship," *Ship and Offshore Structures*, 17(7), pp. 1498-1514.

Du, L., Goerlannd, F., Kujala, P., 2020, "Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from AIS data," *Reliability Engineering & System Safety*, 200, 106933.

Goerland, F., Montewka, J., 2015, "Maritime transportation risk analysis: Review and analysis in light of some foundamental issues," *Reliability Engineering & System Safety*, 138, p. 115-134.

Guarin, L., Hifi, Y., Vassalos, D., 2014, "Passenger Ship

Evacuation – Design and Verification," in 6th International Conference on Virtual, Augmented and Mixed Reality, VAMR 2014 - Held as Part of 16th International Conference on Human-Computer Interaction, HCI International 2014, Heraklion, Crete, Greece.

IMO, 2009, SOLAS-International Convention for the Safety of Life at Sea, London, UK: International Maritime Organisation (IMO).

Kim, S., Taimuri, G., Kujala, P., Conti, F., Le Sourne, H., Pineu, J., Looten, T., Bae, H., Mujeeb-Ahmed M., Vassalos, D., Kaydihan, L., Hirdaris, S., 2022, "Comparison of numerical approaches for structural response analysis of passenger ships in collisions and groundings," *Marine Structures*, 81, 103125.

Mauro, F., Vassalos, D., Paterson, D., Boulougouris, E., "Exploring smart methodologies for critical flooding scenarios detection in the damage stability assessment of passenger ships," *Ocean Engineering*, 262, 112289.

Mauro, F., Vassalos, D., Conti, F., 2023, “Damage surrogate models for real-time flooding risk assessment of passenger ships”, *Ocean Engineering*, 285, 115493.

Montewka, J., Manderbacka, T., Ruponen, P., Tompuri, M., Gil, M., Hirdaris, S., 2021, "Accident susceptibility index for a passenger ship-a framework and case study," *Reliability Engineering & System Safety*, 218, p. 1-22.

Papanikolaou, A., 2009, Risk-Based Ship Design, Berlin/Heidelberg, Germany: Springer-Verlag

Paterson, D., Vassalos, D., Boulougouris, E., 2021, "Results of simulation scenarios as input to the flooding risk model," in FLARE, deliverable D4.4.

Rahola, J., 1939, "The Judging of the Stability of Ships and the Determination of the Minimum amount of Stability,".

Ruponen, P., van Basten-Batemburg, R., van’t Veer, R., Bu, S., Dankowski, H., Lee, G., Mauro, F., Ruth E., Tompuri, M., 2022, "International benchmark study on numerical simulation of flooding and motions of a damaged cruise ship," *Applied Ocean Research*, 129, 103403.

Vassalos, D., 2009, "Risk-Based Ship Design - Methods, Tools and Applications," in Risk-Based Ship Design, Berlin/Heidelberg, Germany, Springler-Verlaag, pp. 17-98

Vassalos, D., 2012, "Design for Safety, Risk-Based Design, Life-Cycle Risk Management," in 11th International Marine Design Conference (IMDC), Glasgow, Scotland, UK,.

Vassalos, D., Paterson, D., Mauro, F., Mujeeb-Ahmed, M., Boulougouris, E., 2022a, "Process, methods and tools for ship damage stability and flooding risk assessment," *Ocean Engineering*, 266, 113062.

Vassalos, D., Paterson, D., Papanikolaou, A., 2022b, "Impact of life-cycle considerations on internal ship layout for damage stability protection," in SNAME 14th International Marine Design Conference, IMDC 2022, Vancouver, BC, Canada.

Vassalos, D., Paterson, D., Mauro, F., Mujeeb-Ahmed, M., Murphy, A., Michalec, R., Boulougouris, E., 2022c, "A lightning intact and damage stability in a multi-level assessment framework," in 18th International Ship Stability Workshop 2022, Gdansk, Poland.

Vassalos, D., Paterson, D., Mauro, F., 2023, “Real-time flooding risk evaluation for ship-to-ship collisions based on first principles”, *Ocean Engineering*, 281, 114847.