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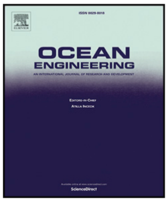

Real-time estimation of the Potential Loss of Life in case of ship-to-ship collisions

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ABSTRACT

The flooding risk assessment for passenger ships is a topic mainly addressed during the design phase of the vessel. However, risk pertains to the whole life cycle of a ship. In this sense, the operational phase requires methodologies for risk assessment while the vessel is sailing, thus a real-time estimation of the flooding risk. The framework developed during the EU project FLARE for the design phase allows for determining flooding risk by estimating the Potential Loss of Life. Such a metric can be extended to real-time applications thanks to the flexibility of the risk framework. The execution of direct calculations for ship-to-ship collisions and flooding simulations for vessel survivability permit the generation of fast surrogate models to determine potential damage dimensions and survivability for a specific event, thus the flooding risk. Such a process, including uncertainties due to the onboard instrumentations, is applied to two reference passenger ships: a Cruise ship and a RoPax. Simulations of four scenarios considering different weather conditions show the real-time variations of the flooding risk (through the Potential Loss of Life) following collision with a target vessel, thus demonstrating the applicability of the process in real time.

1. Introduction

The survivability assessment of a passenger ship after a flooding event has always been identified with the analysis and judgement 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 the 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., 2022c). To this end, risk models for passenger ships should evaluate risk as a combination of both susceptibility 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 principles 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., 2022b) 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 Potential Loss of Life (PLL) as risk metric (Vassalos et al., 2022b).

Such a strategy can be used also for real-time determination of risk onboard passenger ships, using the PLL as indicator of the instantaneous level of risk. This approach has been described by Vassalos et al. (2023) where the basis for the development of a real-time evaluation of the PLL is given. The method uses databases determined by sets of first principle-based calculation for crash analyses (necessary to determine the damage dimensions) and time-domain flooding simulations (describing the Time to Capsize (TTC)) of the vessel in a certain critical

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Nomenclature

AIS	Automatic Identification System
COLREGS	Convention of the International Regulations for Preventing Collisions at Sea.
DSS	Decision Support System
DTC	Distance to Collision
IMO	International Maritime Organisation
FEM	Finite Element Method
FLARE	Flooding Accident Response
FR	Fatality Rate
GPS	Global Positioning System
PLL	Potential Loss of Lives
POB	Person on board
QMC	Quasi-Monte Carlo
SOLAS	Safety of Life at Sea
TTC	Time to Capsize
TTE	Time to Evacuate
TTPC	Time to Possible Collision
WTD	Watertight Doors

scenario. Surrogate models derived from the database allow for evaluating the PLL in real-time. However, the work does not cover an effective demonstration of the process nor the determination of the databases and annexed surrogate models. This, in turn, has been partially covered in Mauro et al. (2023) for the generation of the damage model. The approach is one of the final findings of the EU founded project FLARE, promoting the application of first-principle tools to the estimation of risk of flooding after an accident. The project focuses on different steps of the vessel life-cycle, from the design process to the operation. This study employs relevant findings achieved during the project for the design phase and opens a spotlight on the direct estimation of risk due to flooding events during operations.

In the present work, the procedure for real-time evaluation of the risk through the instantaneous determination of PLL is demonstrated on two passenger ships: a cruise vessel and a RoPax. The study covers the missing part of the previous works presented by the authors. The paper provides an overview of the flooding risk framework applied to PLL in Section 2. Section 3 presents the procedure for the evaluation of the real-time PLL. The reference vessels and calculation scenarios are reported in Section 4, while the results and their discussion are provided in Section 5. The determination of the surrogate models and the method used for the survivability database generation is provided in the appendices.

The paper provides all the information necessary to the calculation of PLL in real time, highlighting the applicability of the method for real-time prediction of flooding risk onboard of passenger ships in case of a potential ship-to-ship collision event.

2. Flooding risk framework

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

$$PLL = p_f \cdot c_f \tag{1}$$

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 in 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. The different values or probabilities related to the occurrence, survivability and fatality rate FR are associated with different levels in the risk evaluation process in a multi-level framework. 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 whilst evacuation analysis determines the fatality. Accordingly, the different levels correspond to different PLL levels as it is described in the following sub-sections

2.1. 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.

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:

$$FR = \begin{cases} 0.8 & \text{if } s = 0 \\ 0.0 & \text{if } s < 1 \end{cases} \tag{2}$$

where s is the s-factor according to the SOLAS framework. 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 passenger ship survivability assessment are transient capsizes (Paterson et al., 2021), which means conditions where no time for evacuation is available.

2.2. 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:

$$FR = \begin{cases} 0.0 & \text{if } TTC > n \\ 0.8\left(1 - \frac{TTC-n}{30-n}\right) & \text{if } 30 \leq TTC \leq n \\ 0.8 & \text{if } TTC < 30 \end{cases} \tag{3}$$

where n is the maximum allowable evacuation time in minutes according to MSC.1/Circ. 1533. Therefore, the assumption of Eq. (3) 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 ship evacuation simulation where motions and floodwater imported in the evacuation software and accounted for as

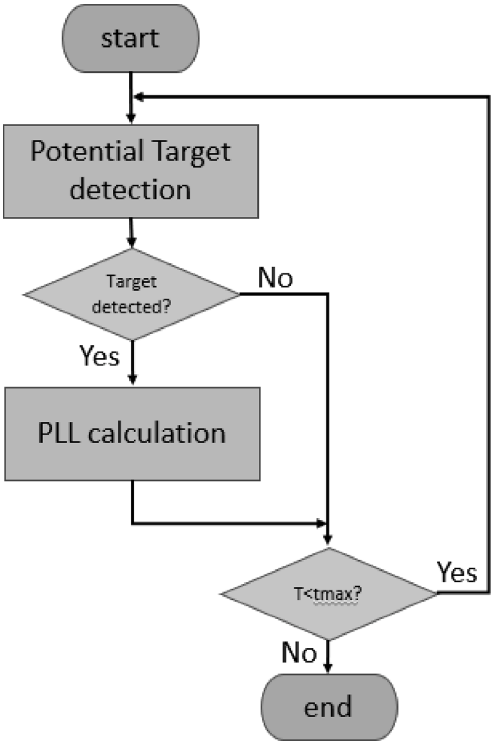

Fig. 1. Flowchart showing the steps for real-time PLL estimation (Vassalos et al., 2023).

flooding hazards during the evacuation process. Such a coupling allows for a direct comparison between the time taken for evacuation process TTE and the associated TTC.

Thanks to this multi-level framework, the single definitions of probabilities for evaluating 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.

3. Methodology for real-time PLL calculation

The scope of a real-time PLL calculation is to enable the crew to quantify the gravity of the consequence of a potential accident in terms of loss of lives. Such a task is a pioneering attempt to make a step forward from the state-of-the-art emergency detection systems, where only few examples are available in literature for voyage simulations (Ruponen et al., 2022b, 2020). The methods developed in these studies refer to the concept of accident susceptibility (Montewka et al., 2021), thus referring to a qualitative scale (from negligible to very high) to identify the attitude of a ship to be potentially subjected to a hazard. Susceptibility is then associated with vulnerability according to the adoption of key performance indicators (A^* and r^*) derived from static calculations with different opening status of the watertight doors (WTD). To pursue and promote the application of direct methods, the last part of the process should be substituted by the estimation of PLL in real time. Then the simulation process should follow the steps described in Fig. 1. This process is equivalent in the case of a computer simulation or an onboard tool for real-time PLL estimation (Vassalos et al., 2023).

3.1. General process

Software for real-time risk estimation onboard of passenger ships, or ships in general, should be capable of performing the following two main tasks, here limited to the ship-to-ship collisions as the sole hazard analysed in the study:

1. Identify potential ship-to-ship collisions.
2. Evaluate the risk levels associated with the detected collision.

Optionally, the process can be linked to the provision of possible countermeasures to reduce risk, but this is not here analysed as part of an onboard decision support system (DSS), nor included in the scope of the present study.

The developed approach is oriented to solve the real-time PLL calculation problem before an accident occurs. It is, certainly, extremely interesting also to understand the risk during an emergency, thus after a collision. However, such an extension requires the evaluation of the evacuation path through complex and time-consuming analyses that gave a marginal added value to risk identification during preliminary calculations performed in project FLARE (Guarin, 2021). Therefore, the proposed process will cover real-time PLL calculation only for the before an accident case, implementing computer-based simulations reproducing the system described in Fig. 2, which includes the following subsystems:

Onboard instrumentation: this is the system devoted to input data acquisition. As the effective characteristics of the onboard instrumentation are not known at this stage, the proposed process is not considering the simulation of the onboard system and precalculated data are used as direct inputs to successive blocks.

Collision detection system: this block evaluates the possibility of collision with another ship detected by the onboard instrumentation.

Damage model: the damage model is the block devoted to the prediction of the damage dimensions associated with the possible future collision event.

PLL model: this is the model that performs all the calculations needed to estimate PLL from the damage dimensions and locations provided by the damage model.

The following sections describe the modelling of the single individual blocks in Fig. 2 necessary to determine the PLL in a real-time virtual environment for simulation purposes. The basis of some of the methodology follows the framework descriptions given in Section 2 but with some adaptations necessary to simulate a real-time event.

3.2. Collision detection

Collision detection problems may be faced with different levels of accuracy and fidelity, considering the simulation and prediction of the possible path of both the own ship and targets, or just considering a simple extrapolation of the current state of the detected vessels. With the process under development in an early stage of definition, a simple approach is here used for validation purposes, as the main target is not on the collision algorithm but the real-time PLL determination.

Therefore, a possible occurrence of the collision can be estimated using the evaluation of minimum distance (DTC) and time to possible collision (TTPC) (Zang et al., 2021). Assuming a Cartesian reference system centred on the ship, the DTC can be estimated as follows:

$$DTC(t,\tau) = \sqrt{\left(x_{s,\tau} - x_{o,\tau}\right)^2 + \left(y_{s,\tau} - y_{o,\tau}\right)^2} \qquad \text{for } t < \tau < T_{max} \tag{4}$$

where $\left(x_s, y_s\right)$ and $\left(x_o, y_o\right)$ are the estimated positions of the ship and the detected target at future time instant τ until a maximum time T_{max}. For the present study, T_{max} is set to 30 min and the time intervals have an order of 1 s each. This means the search is restricted to collisions that may occur in the next half hour of navigation on the same route. However, the minimum distance is not sufficient to identify the collision, as it only gives an indication of the proximity of the two objects, and especially for large time steps does not ensure that the two

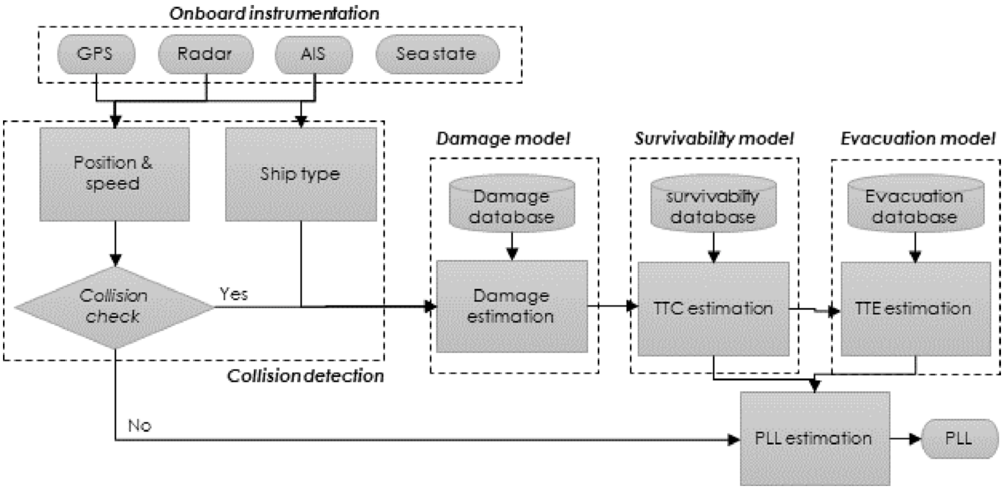

Fig. 2. On-board real-time risk estimation outline before accident occurrence (Mauro et al., 2023).

trajectories intercept each other at a specific time. It is then mandatory to define an additional quantity related to time, namely the TTPC:

$$TTPC\left(t,\tau_i\right) = \frac{DTC\left(t,\tau_i\right)}{\frac{DTC(t,\tau_i)-DTC(t,\tau_{i-1})}{\tau_i-\tau_{i-1}}} \text{ for } 2 < i < N_\tau \tag{5}$$

where N_τ is the number of extrapolated time intervals. Adopting Eqs. (4) and (5) for the assessment of a collision, implies selecting criteria for the identification. In this study, the change of sign for Eq. (5) has been selected as the first choice. A change of sign in the time series of TTPC implies that the two trajectories have intersected each other. Other methodologies, like the COLREGS method (Zang et al., 2021), do not strictly require this check, as they work with the proximity of the objects to determine the susceptibility of an accident. The present study does not consider directly the prediction of an evasive manoeuvre of the target ship as the prediction is made in real-time. So, an immediate change of track by the target ship is identified directly by the onboard instrumentation. However, as the system should be capable to predict the future path of the vessel, the occurrence of a possible evasive manouvre can be considered in further developments of the proposed methodology.

From the collision check, an estimate of the possible position, speed and encounter angle of a target object can be determined and used as an input for the PLL estimation in real time. The process evaluates the relative angle β_T between the two colliding objects as a function of the time and estimates the x_D of the collision, which means the hypothetical longitudinal position of the breach centre. The process can be described as follows:

$$x_D = x_s + \left(L_o - x_o\right) \cos \beta_T \tag{6}$$

where L_o is the length of the target ship and x_s and x_o are the estimated positions of the command bridge for the own and target ship. For the own ship, this is approximated at $2/3L_s$, whilst for the target ship it depends on the vessel type. However, as a simplistic preliminary approach, both quantities can be set to midship.

3.3. Risk level evaluation

The PLL can be used as the measure of flooding risk. Such an option for a real-time risk estimation implies, as already highlighted in Vassalos et al. (2023), developing a database approach to determine each component of the PLL, namely:

$$PLL_i = p_{hz_i} p_i \left(1 - s_i\right) FR_i POB \tag{7}$$

where POB are the persons on board. As the modelling is oriented to real-time detection of a collision, the probability of the hazard p_{hz} can be neglected from the calculation as it is assumed that the collision has occurred, thus the probability is equal to 1. The same is the case for the scenario probability p and for the survivability s. In fact, the concept of survivability is intrinsic in the Time to Capsize (TTC), and TTC is necessary to determine the FR_i, whilst taking into account POB. As already underlined in Vassalos et al. (2023), the most suitable way to evaluate PLL for real-time applications is by adopting the Level 2-1 method, described in Section 2, which is giving an analytical expression for FR_i as a function of TTC through equation (3). The application of Eq. (3) requires the adoption of a database approach to determine the TTC. Such an approach is possible only if another database with possible occurring breach dimensions is available. The following subsections provide a rough description of the damage and TTC models, focusing on the inputs and outputs needed. A fully detailed description of the databases and the methodologies applicable to generate fast surrogate models for PLL calculations is given in Vassalos et al. (2023) and Mauro et al. (2023).

3.3.1. Damage breach model

The damage breach model for a real-time risk assessment should be based on databases of direct calculations composed of outputs deriving from crash simulations. A detailed description of the methods used to develop the damage database is provided in Mauro et al. (2023). However, for the sake of clarity, a brief description of the process is provided hereafter.

The damage breach model start from the definition of a breach according to a box-shaped object. The breach dimensions derive from direct crash calculations, performed with super-element or FEM codes. The process generates a distribution of damage dimensions, derived from a uniform set of initial parameters used to initialise the collision calculations (Mauro et al., 2023). The resulting set of damage dimensions (the length L_D, the penetration B_D, the lower vertical limit z_{LL} and the upper vertical limit z_{UP}), are then used as an input to a regression model. In the specific, the current applied methodology employs the software SHARP (Le Sourne et al., 2012), a super-element code capable of simulating ship to ship collisions according to a predetermined set of initial conditions. For this reference study, the following initial conditions have been considered:

- Stricking ship speed: five speeds (from 2 to 10 m/s in steps of 2 knots) have been considered adopting a stratify option for the database generation.
- Ship type: 11 ship types have been considered as reported in Mauro et al. (2023).
- Struck ship speed: all the calculations have been performed supposing the struck speed equal to zero (Conti et al., 2022).

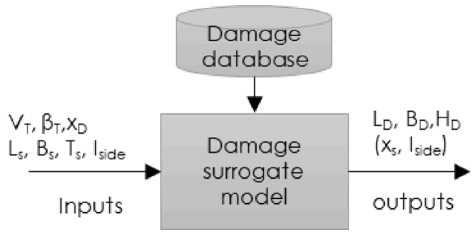

Fig. 3. Damage model schematisation with inputs and outputs.

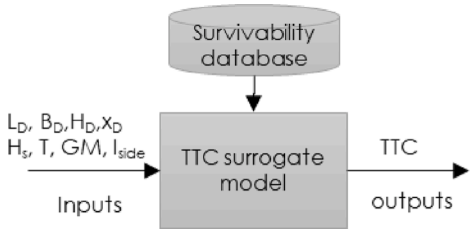

Fig. 4. Survivability model schematisation with inputs and outputs.

- Longitudinal position of the impact: the calculations have been performed on 500 locations between 0.2 and $0.8L_{PP}$, selected according to a quasi-random process.
- Collision angle: the calculations have been performed on 500 quasi-random samples, considering angles from 20 to 90 degrees.
- Striking ship draught: 3 draught have been considered with a stratified option for the damage generation.
- Struck ship draught: 3 draught have been considered with a stratified option for the damage generation.

According to these settings the database for the implementation of surrogate model has been developed.

Furthermore, besides the generation of the database itself, the 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 has also be defined in Mauro et al. (2023), providing alternatives with different confidence levels.

The procedure can handle different kind of regression techniques, starting from white-box models like multiple linear regressions, up to black-box models like the random three forest. A detailed description of the process is provided in Mauro et al. (2023). Regardless of the regression methodology used to define the damage model, the output of the surrogate model is a tuple of damage dimensions referring to the possible collision detected by the collision detection module. A schematisation of the damage model is shown in Fig. 3.

From the collision detection model, the values and indicators that are provided to the damage model are the striking ship speed V_T, the collision angle β_T, the collision location x_D, the side identifier I_{side} and the striking ship main dimensions (L_s, B_s and T_s). The provided outputs of the damage model are the principal geometric characteristics of the collision damage, i.e. the damage length L_D, the damage penetration B_D, upper and lower limits z_{LL} and z_{UP}. The value $H_D = z_{UP} - z_{LL}$ is used in the surrogate model, as it provides a better fitting for the generated models (Mauro et al., 2023).

The damage model is capable of handling individual inputs, providing single damage as an output but can also handle distributions of input variables, and, consequently, generate distributions of damage dimensions. Such a capability has a key role in the uncertainty modelling that will be described subsequently.

3.3.2. TTC 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 Eq. (7), necessary to evaluate the case occurrence, the survivability, and the fatality rate. In a real-time risk assessment, the process is not exactly the same, as the concept of occurrence is no longer related to the probabilistic distributions of the damages and on the environmental conditions described in the probabilistic approach to PLL calculation. The occurrence is determined by the collision detection model, which means that once collision is predicted, p is equal to 1, 0 otherwise. More precisely, the effective p is given by the distribution of values provided by the collision model, thus it is inherited in the PLL model too.

The PLL model can then be split into two sub-models, one for the survivability and one for the fatality rate FR, to be applied in cascade. The survivability model is schematised in Fig. 4 with the associated surrogate model that should be applied here for the same reasons indicated for the damage model. As highlighted by several studies (Mauro et al., 2022b,a), 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. Here, a general description of the parameters used to define the parameters and the surrogate model is given.

The generation of the database, as it was for the damage model, implies te selection of a set of parameters to change systematically in order to identify the conditions at which evaluate survivability. As described in the previous section, the damage model provides indications concerning the damage dimensions, either considering a single damage or a distribution of damages. As such, the survivability model should be capable of reading the provided inputs, together with other information relevant to damage stability calculations. The inputs to the model are the damage dimensions (L_D, B_D, z_{LL} and z_{UP}) and the damage location x_D derived from the damage model, the loading condition of the ship (means the draught T and the GM value) and the actual sea state (in the form of significant wave height H_s). The generation of the database necessary to develop the survivability surrogate model should follow the philosophy adopted for the damage model, considering the availability of data derived from the surrogate damage model. In fact, the database should consider all the possible variations of the variables provided by the damage model. Then, the following conditions have been considered for this study:

- Damage location x_D: the damage location derive from an uniform distribution covering the whole length of the ship.
- Damage length L_D: the damage length is considered uniformly distributed between the maximum limits provided by the SOLAS regulation.
- Damage penetration B_D: the damage penetration is considered uniformly distributed between the limits provided by the SOLAS regulation.
- Damage vertical upper limit z_{UP}: the vertical upper limit is considered uniformly distributed between the limits provided by the SOLAS regulation.
- Damage vertical lower limit z_{LL}: the vertical lower limit is considered uniformly distributed between the limits provided by Bulian et al. (2019).

Calculations should be performed for both port and starboard side. The methodology used for the determination of the database is different from the commonly used definition of damages employed by SOLAS or other conventional damage stability framework. Such a difference is due to the necessity of provide values for the TTC for any possible combination of damage parameters that may occur for a possible damages, regardless from the statistics of accidents from witch statutory calculations derive. The complete methodology used to generate the survivability surrogate model is described in detail in Vassalos et al. (2023), employing the damage location and dimensions, the vessel loading condition, and the environmental conditions as input and providing the TTC as principal output. Statistics can be carried out also on other outputs of dynamic simulations, like survivability or risk detection criteria (Mauro et al., 2022b). However, for the simulation of a PLL real-time calculation, the TTC is the most relevant output and is, therefore, the sole output considered for the survivability model through this study.

3.4. Real-time PLL calculation

The direct application of the damage and survivability model, as described in the previous sections, allows for the detection of a single value of TTC if a single set of inputs were provided to the initial damage model. Consequently, by evaluating the fatality rate FR with Eq. (3) with the proper assumptions concerning survivability and hazard occurrence, a single value for the PLL is derived. For convenience, we can refer to the application of the survivability model and Eqs. (3) and (7) as the PLL model.

However, the evaluation of a single PLL value is certainly convenient to provide a unique real-time output to a DSS or a generic collision detection system mounted on-board but is not taking into account possible errors and inaccuracies of the inputs. To this end, it is important to model such uncertainties while keeping the final output as a unique value for efficient usage by operators and practitioners. Proper modelling of errors and uncertainties requires knowledge of all the sensors and measuring systems installed onboard and involved in the collision detection tool. However, at this stage of development, such kind of information is still unknown and may be also ship-dependent and, consequently, some approximations have to be considered. For this purpose, here a general model based on a Gaussian distribution error on the initial input value is considered, being sufficiently general to be further extended and modified in consequence of future and more detailed studies. According to the Gaussian error, each one of the inputs to the damage model follows the following distribution:

$$p(x_i) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{1}{2}\left(\frac{x_i-\mu}{\sigma_i}\right)^2} \tag{8}$$

where μ_i is the original input value to the model (interpreted as the mean value of the process) and σ_i is the associated standard deviation, simulating an uncertainty on the mean value. The values modelled with this uncertainty are 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 this study have been set to 1.5 knots for the speed, 10 metres for the breach position and 5 degrees for the collision angle. As the values are arbitrary, they should not be proposed as real values to use in an onboard tool, it is just a reference input used to test and demonstrate the applicability of the real-time PLL calculation.

As a result of the application of Eq. (8) to the inputs, the initial dataset entering in the damage model is no more composed of a tuple of data but instead of a tuple of probabilistic distribution of data, having equation (8) as marginal probability density function. In the absence of additional indications on possible couplings between the uncertainty levels of two or more inputs, the distributions are here supposed to be independent random variables.

Having implemented uncertainties in the inputs, the PLL calculation process should be capable of handling distributions and no more single values. Therefore, to have again a single value of PLL as an output of the process, a possible solution is to obtain the real-time PLL value as a Quasi-Monte Carlo (QMC) integration process on a sample of input values. The QMC is preferred to a conventional crude Monte Carlo method as it is capable to reach convergence with a lower amount of samples (Mauro and Vassalos, 2022). The QMC approach leads to the final calculation of PLL with the following formulation:

$$PLL \approx \frac{1}{N_{QMC}} \sum_{i=1}^{N_{QMC}} PLL_i\left(x_{D_i}, V_{T_i}, \beta_{T_i}\right) \tag{9}$$

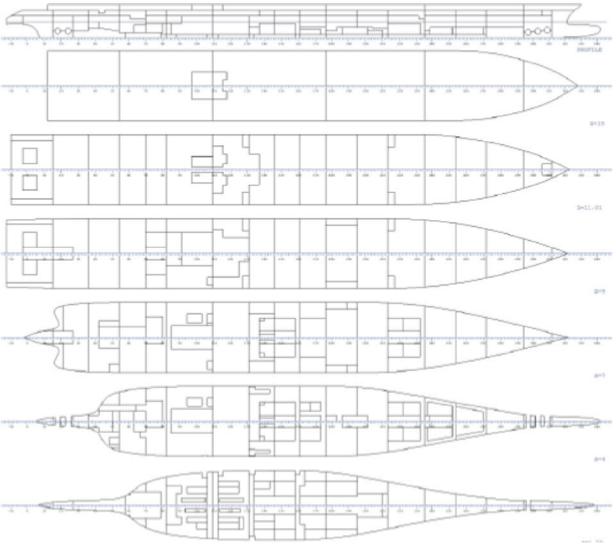

Fig. 5. Reference cruise ship internal layout.

The process described by Eq. (9) should be applied to a sample of N_{QMC} quasi-random numbers, otherwise, adopting conventional pseudo-random numbers (the crude Monte Carlo), the PLL value will be no more unique unless performing millions of calculations. Here the adoption of Sobol sequences (Sobol et al., 2011) allows for the reduction of N_{QMC} up to a value of 1000, ensuring convergence of the final integration.

4. Reference ships and scenarios

The present section describes the reference ships and reference cases used to test and demonstrate the applicability of the real-time PLL calculation process previously described. First, the two reference vessels are introduced with the comparison of the main characteristics and indication of the source of databases for damage dimension and TTC used in this study. Subsequently, the four scenarios selected for the demonstration of the process are described, considering the environmental conditions and reference striking ships involved in the simulations. The scenarios refer to an arbitrary case, with no connection to an effective accident for the reference ship. This is not an issue as the scenarios have been selected for demonstration purposes of the method, in such a way to identify the differences in estimated PLL with two different vessel types (one cruise ship and one Ro Pax) on the same case.

4.1. Reference vessels

The aim of this study is to demonstrate the applicability of the real-time PLL calculation for passenger ships. To this end, two reference ships have been identified to apply the process described in Section 3, one Cruise ship and one RoPax.

The reference Cruise ship is a ship used during EU project FLARE for benchmarking purposes (Ruponen et al., 2022a) and intensively analysed for survivability studies in waves (Mauro et al., 2022b,a; Mauro and Vassalos, 2023). For this ship, the survivability database is already available but the damage database has been scaled from a similar ship employed for crash analysis (Conti et al., 2022; Mauro et al., 2023). Table 1 presents a summary of the main characteristics of the reference cruise ship, while Fig. 5 shows the internal layout used for the survivability analyses and Fig. 6 the simplified super-element model for the crash analyses.

The RoPax model refers to a sample ship available in NAPA. The main characteristics of the vessel are listed in Table 1, while the

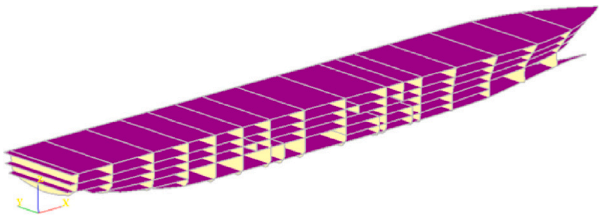

Fig. 6. Reference cruise ship super-element model.

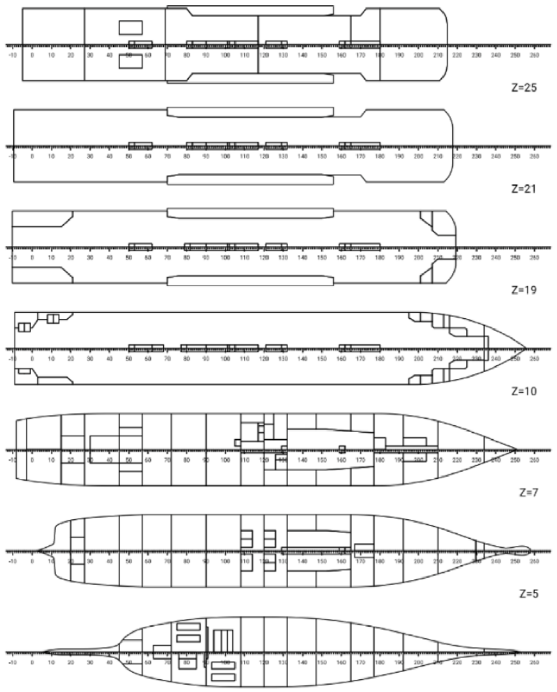

Fig. 7. Reference Ro Pax internal layout.

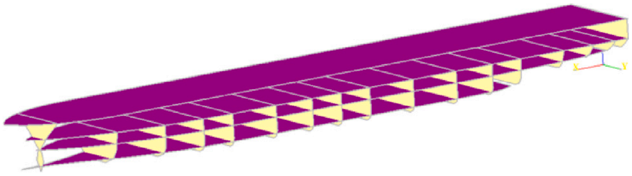

Fig. 8. Reference Ro Pax super-element model.

internal layout is visible in Fig. 7 and the super-element model in Fig. 8. It can be observed that the granularity of the internal layout of the RoPax model is too rough for conventional damage stability analyses in time-domain. However, it is enough for the scope of this demonstration.

The surrogate models derived for the TTC and the damage dimensions are reported in Appendix A and Appendix B for the cruise ship and RoPax, respectively. The surrogate models for the TTC have been obtained for calm water and significant wave heights ranging from 1 to 4 metres, while crash analyses considers the ship symmetrical between port and starboard side. The surrogate models have been generated according to three strategies: multiple linear regressions, neural networks and tree forests. The methodology employed is well described in Vassalos et al. (2023), Mauro et al. (2023).

Table 1
Main characteristics of the reference cruise ship and reference Ro Pax.

Quantity	Cruise ship	Ro Pax	Unit
Length overall	300.0	220.0	m
Subdivision length	270.2	207.5	m
Breadth	35.2	25.0	m
Design draught	8.2	7.2	m
Calculation GM	3.50	2.35	m
Number of passengers	2750	1900	–
Crew members	1000	100	–

Table 2
Waypoints position and reference speed for the own ship and the target ship.

Waypoint	Own ship			Target ship		
	X (m)	Y (m)	V (kn)	X (m)	Y (m)	V (kn)
WP1	0	0	19	0	3000	15
WP2	1000	0	20	1000	2500	15
WP3	2000	0	18	2000	1500	15
WP4	2750	500	15	3000	1000	13
WP5	5000	700	19	4500	0	12

Table 3
Main dimensions of the target ships.

Quantity	Target#1	Target#2	Unit
Length overall	110.0	221.0	m
Breadth	19.5	30.0	m
Maximum draught	7.6	6.9	m
Depth	10.6	15.3	m
Displacement	11 064	30 114	ton

4.2. Reference scenarios

Besides the selection of the reference ships, it is necessary to define also the scenarios needed to test the real-time PLL calculation process for demonstration purposes. As the instrumentation part is not modelled (see Section 3.2), it is not necessary to use a record of AIS data or radar recordings but is sufficient to generate a signal for the discrete time steps of the simulations. The reference signal should contain the input needed for the calculation of real-time PLL, thus the dimensions of the striking ships (the target), speed and position. It is not necessary to provide the heading of the target as it is automatically calculated by the difference of two contiguous time steps.

The same data for the position and speed should be generated also for the own ship, otherwise, the algorithm for the collision detection cannot provide an estimate of the possible cross of the two vessel paths. To this end, two concurrent routes have been generated based on five waypoints each. The two routes necessitate also of a speed target for both target and own ship, in such a way as to determine the extrapolation of the object's position with time. It has been decided to keep waypoints and reference speeds constant between the reference cruise ship and RoPax. Table 2 shows the waypoints location and the ship speeds, while Fig. 9 portrays the two concurrent paths and the waypoints adopted.

The scenario definition requires the change of parameters for the environmental conditions and the dimensions of the target ship, to check differences between survivability and damage databases between the analysed cases. Two different significant wave height H_s values are then considered: 1.5 and 3.5 metres, respectively. These values have been selected to activate the interpolation process between the calculated surrogate models for TTC (0, 1, 2, 3 and 4 of H_s as reported in Appendices A and B). Concerning the target ships, two different vessels of the collision database (Mauro et al., 2023) have been selected, representing a chemical vessel (target#1) and a RoPax vessel (target#2) having the dimensions reported in Table 3. The final resulting scenarios are then summarised in Table 4.

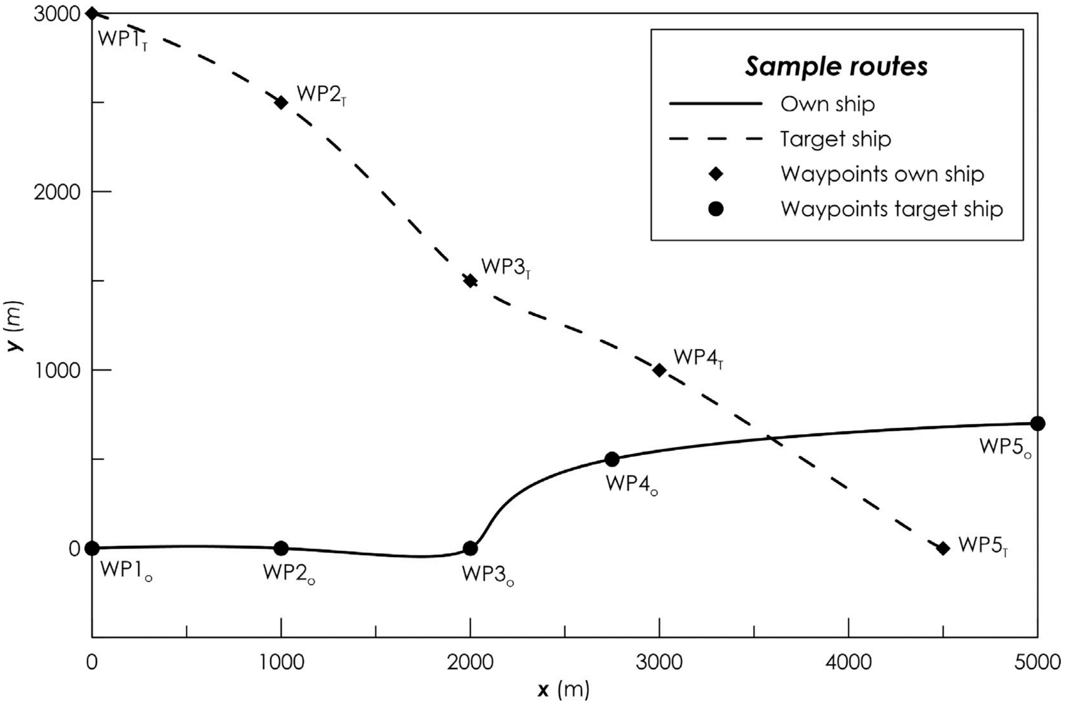

Fig. 9. Sample routes for the own ship and the target ship used for the demonstration.

Table 4
Reference scenarios for real-time PLL calculation.

Scenario	Own ship	Target ship	H_s (m)
Scenario 1 cruise	cruise ship	target#1	1.5
Scenario 2 cruise	cruise ship	target#1	3.5
Scenario 3 cruise	cruise ship	target#2	1.5
Scenario 4 cruise	cruise ship	target#2	3.5
Scenario 1 RoPax	RoPax	target#1	1.5
Scenario 2 RoPax	RoPax	target#1	3.5
Scenario 3 RoPax	RoPax	target#2	1.5
Scenario 4 RoPax	RoPax	target#2	3.5

5. Results and discussion

The present section describes the reference cases performed to evaluate the real-time PLL calculation with the provided database approach. The two reference ships have been used through the reference scenarios.

5.1. Cruise ship

The test cases for the cruise ship have been performed at first, taking into account the four scenarios described in the previous section. In the following, an overview of the results is given also in graphical form. The main considerations are as follows:

Scenario 1 Fig. 10 (top) shows the results of the simulations on the first scenario for the cruise ship case. The scenario refers to the lower wave height case of 1.5 metres and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned points.

Scenario 2 Fig. 10 (bottom) shows the results of the simulations on the second scenario for the cruise ship case. The scenario refers to the higher wave height case of 3.5 metres and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned way-points. Compared to Scenario 1, the detected PLL level is higher due to the lower survivability (lower TTC) of the higher sea state. This is reasonable as all the other parameters for PLL determination are the same as in Scenario 1.

Scenario 3 Fig. 11 (top) shows the results for the third scenario of the cruise ship case. The scenario refers to the lower wave height case of 1.5 metres and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned waypoints. The PLL level is higher than Scenario 1, as the striking ship (the target) is different, resulting in different x_D determination, leading to a higher criticality compared to the previous cases. It has to be noted that the points where the collision angle is close to 90 degrees occur for possible contacts at the ship's fore-end, thus resulting in less critical cases than other conditions.

Scenario 4 Fig. 11 (bottom) shows the results of the simulations on the fourth scenario for the cruise ship case. The scenario refers to the higher wave height case of 3.5 metres and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned waypoints. Compared to Scenario 3, the detected PLL level is higher due to the lower survivability (lower TTC) of the higher sea state. This is reasonable as all the other parameters for PLL determination are the same as in Scenario 3.

5.2. RoPax vessel

The test cases for the RoPax vessel have been performed following the cruise ship, taking into account the four scenarios described in the previous sections. In the following, an overview of the results is given also in graphical form.

Scenario 1 Fig. 12 (top) shows the results of the simulations on the first scenario for the Ro Pax case. The scenario refers to the lower wave height case of 1.5 metres and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned waypoints. Compared to the cruise vessel case, this case is less critical for the detected PLL, due to the different nature of the damage and survivability databases.

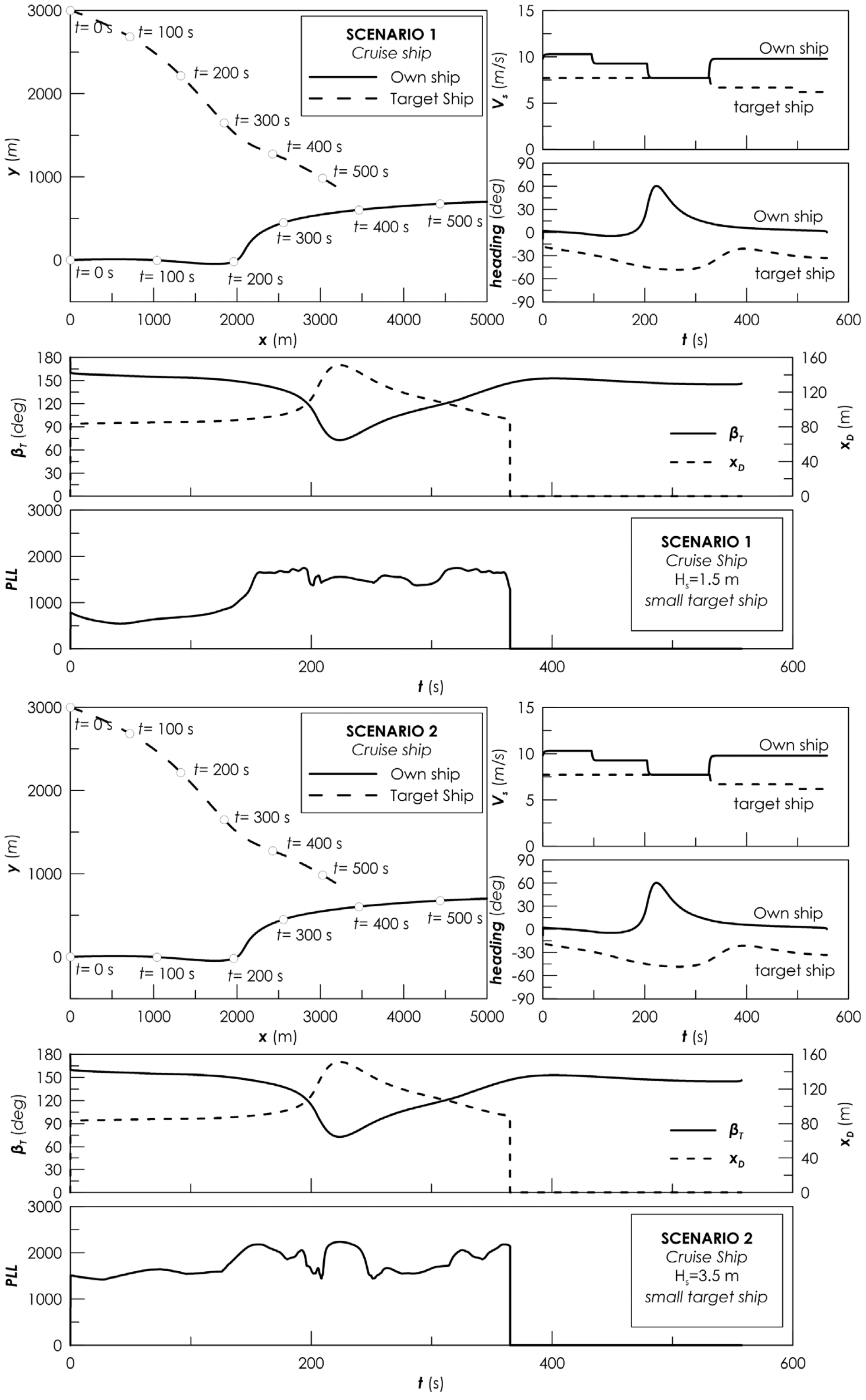

Fig. 10. Scenario 1 (*top*) and Scenario 2 (*bottom*) for the reference cruise ship.

Scenario 2 Fig. 12 (bottom) shows the results of the simulations on the second scenario for the Ro Pax case. The scenario refers to the higher wave height case of 3.5 m and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned waypoints. Compared to Scenario 1, the detected PLL level is higher due to the lower survivability (lower TTC) of the higher sea state. This reflects the trend noticed for the cruise ship for the same scenarios.

Scenario 3 Fig. 13 (top) shows the results of the simulations on the third scenario for the Ro Pax case. The scenario refers to the lower wave height case of 1.5 m and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned waypoints. The PLL level is higher than Scenario 2, as the striking ship is different, resulting in a different x_D determination, leading to higher criticality compared to the previous cases. As already highlighted for the Cruise ship cases, it has to

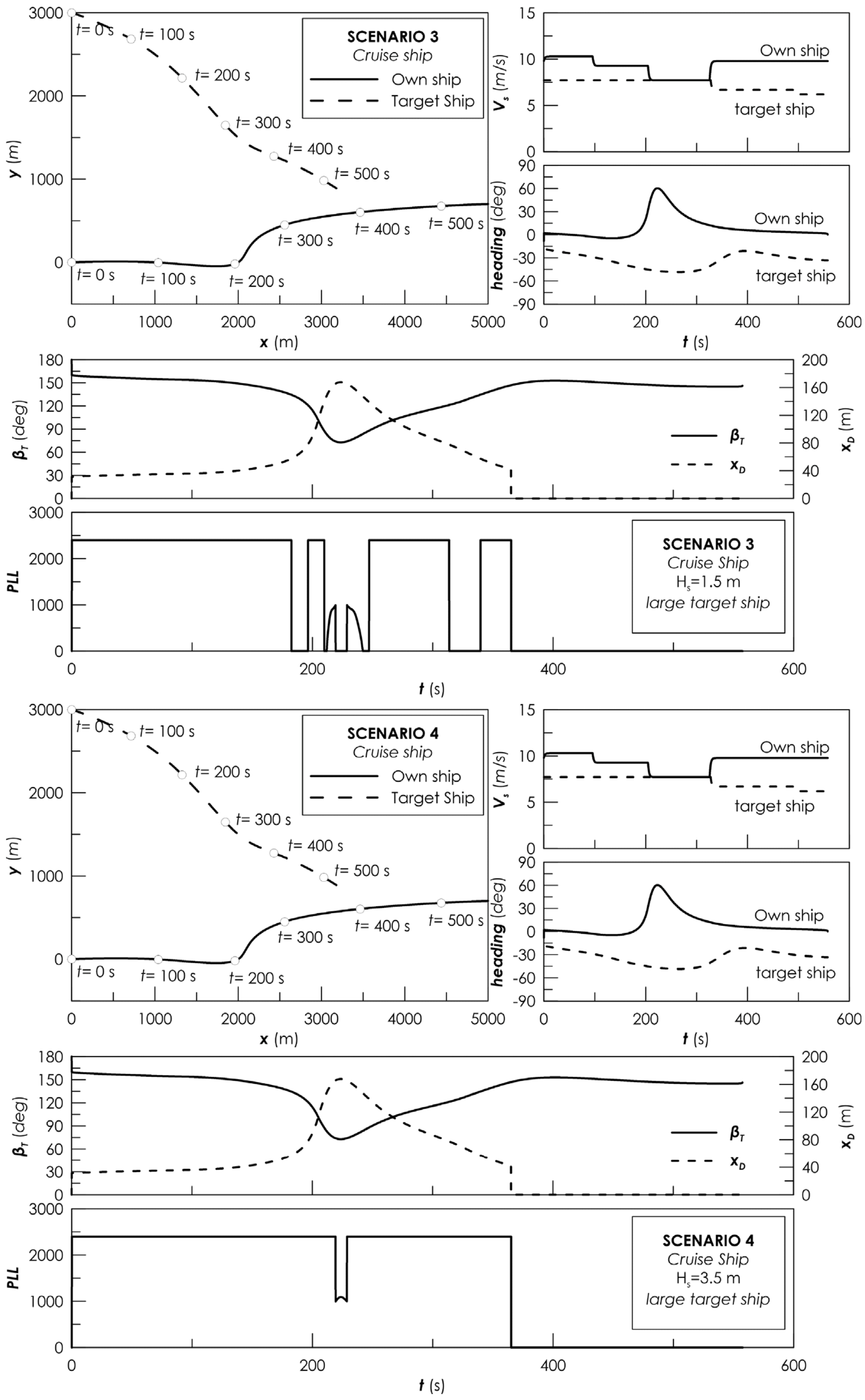

Fig. 11. Scenario 3 (*top*) and Scenario 4 (*bottom*) for the reference cruise ship.

be noted that the points where the collision angle is close to 90 degrees occur for possible contact at the ship's fore-end, thus resulting in being less critical than other conditions.

Scenario 4 Fig. 13 (bottom) shows the results of the simulations on the second scenario for the Ro Pax case. The scenario refers to the higher wave height case of 3.5 m and it is possible to observe the variability of the PLL level as the vessel is manoeuvring through the assigned waypoints. Compared to Scenario 1, the detected PLL level is higher due to the lower survivability (lower TTC) of the higher sea state. This is reasonable as all

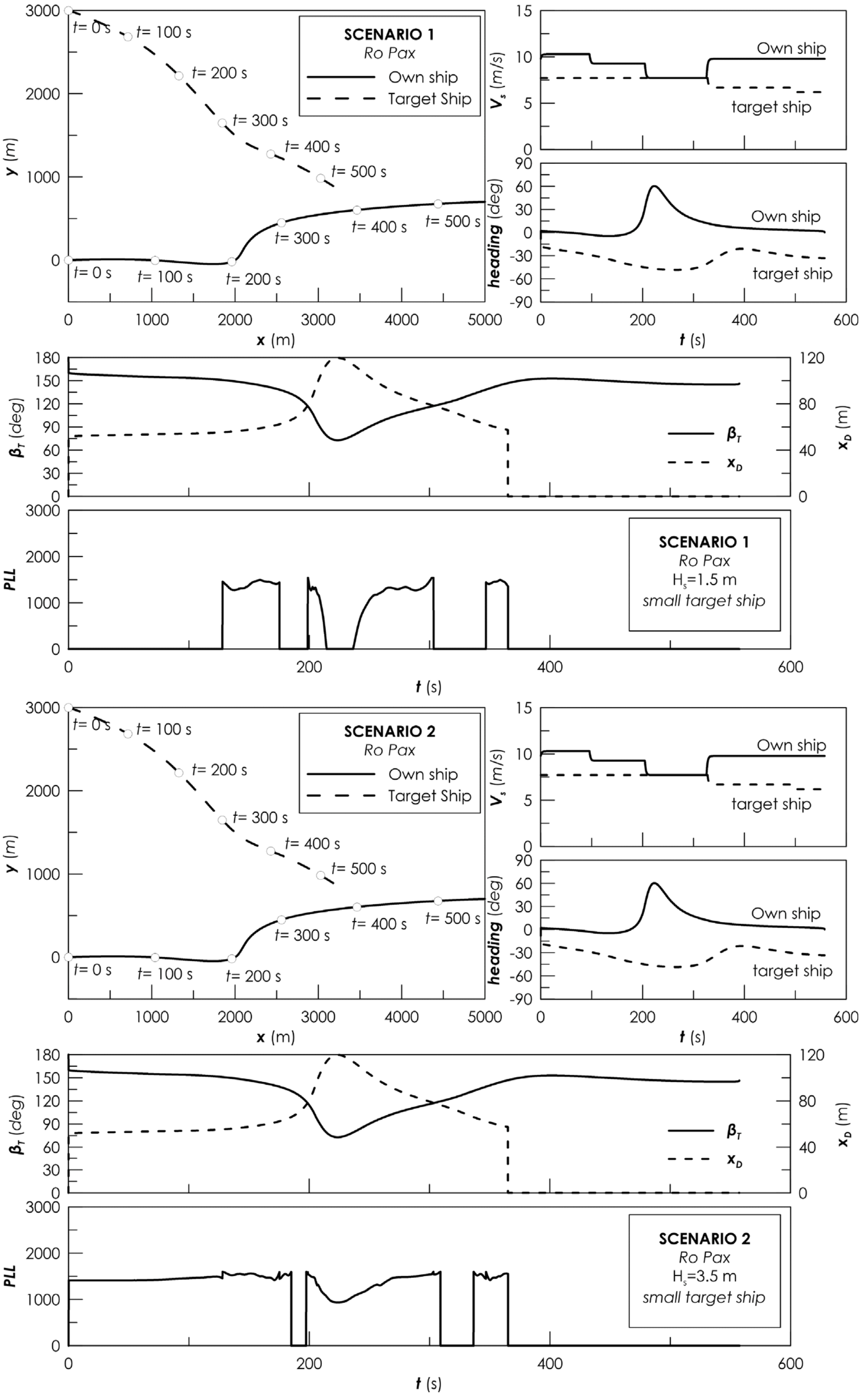

Fig. 12. Scenario 1 (*top*) and Scenario 2 (*bottom*) for the reference Ro Pax ship.

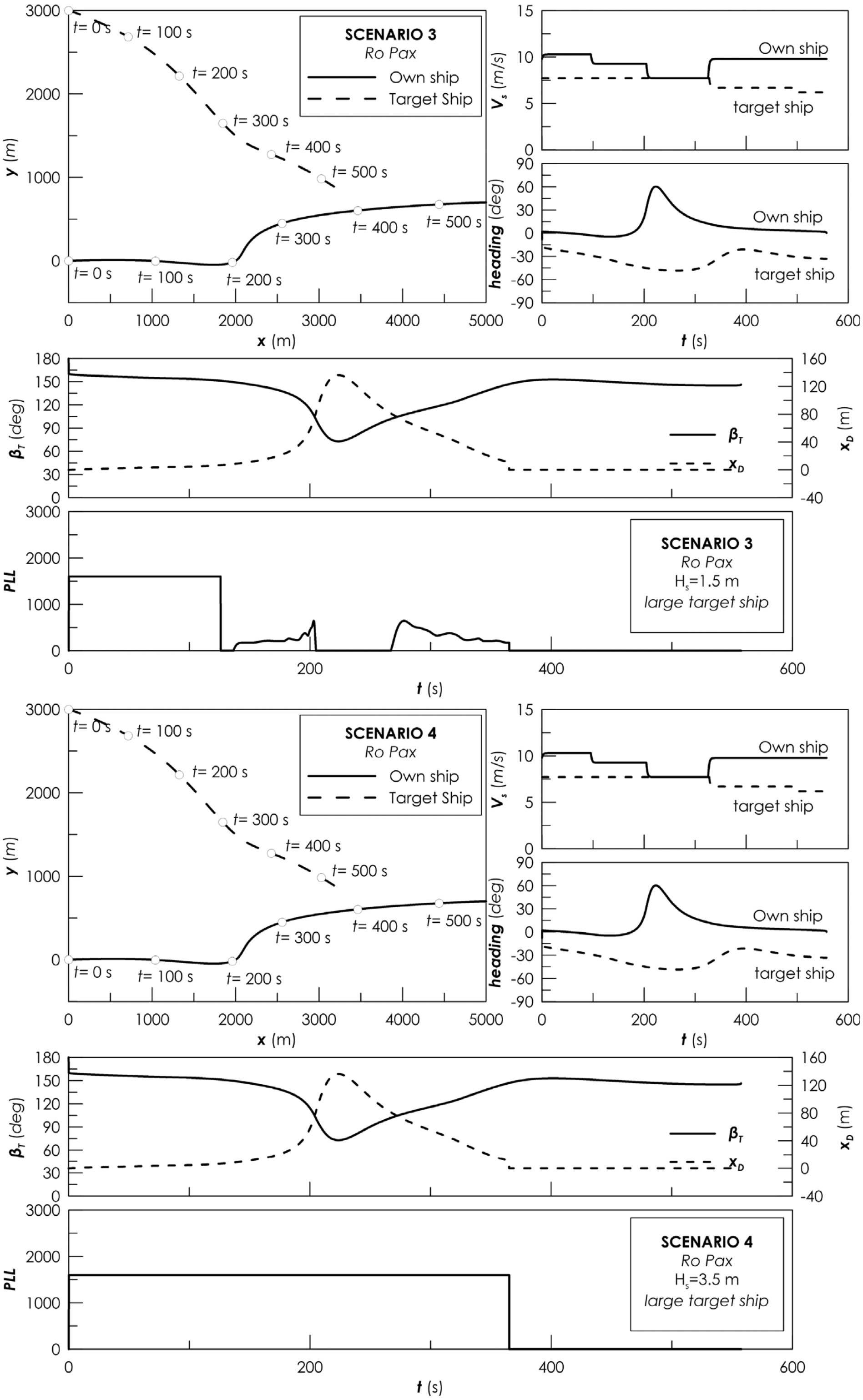

Fig. 13. Scenario 3 (*top*) and Scenario 4 (*bottom*) for the reference Ro Pax ship.

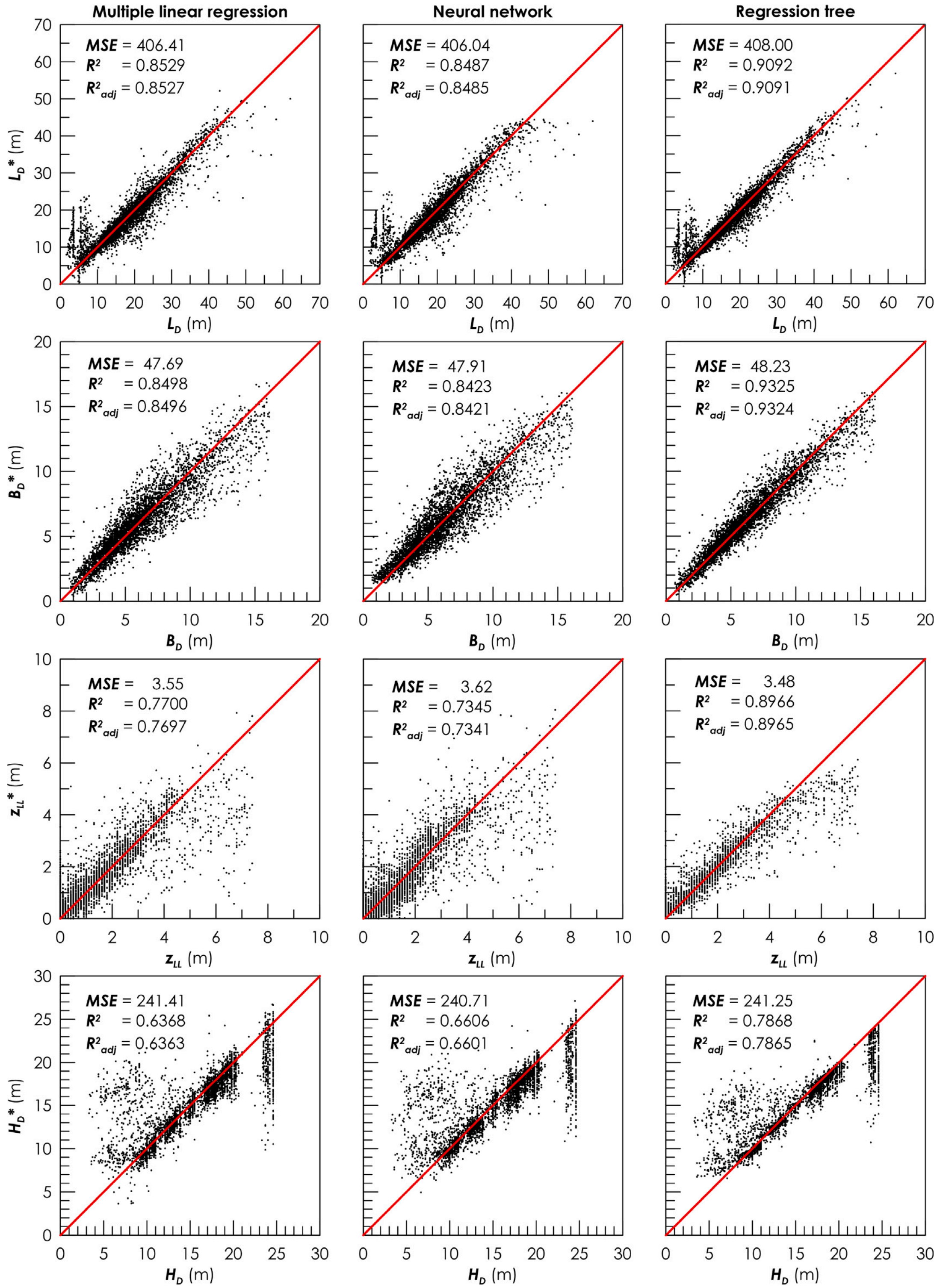

Fig. 14. Damage dimensions surrogate models, observed vs predicted values.

the other parameters for PLL determination are the same as Scenario 3.

5.3. General remarks

The simulations have been performed employing a surrogate model derived from polynomial regression for the damage dimensions. As the quality of polynomial regression is not that high for both ships concerning survivability, the surrogate models for TTC refer to random tree forests. The application of a random tree forest is slowing down the process by about 10 times compared to a simple polynomial model but increases the reliability of the obtained results. Preliminary testing shows that a single-time step calculation of PLL including uncertainty (thus with the 1,000 Quasi Monte-Carlo samples) requires about 0.03 s employing polynomial models only. The introduction of the forest tree for TTC estimation requires between 0.2 and 0.3 s for the estimation. This is not an issue while considering a time step of 1 s due to the

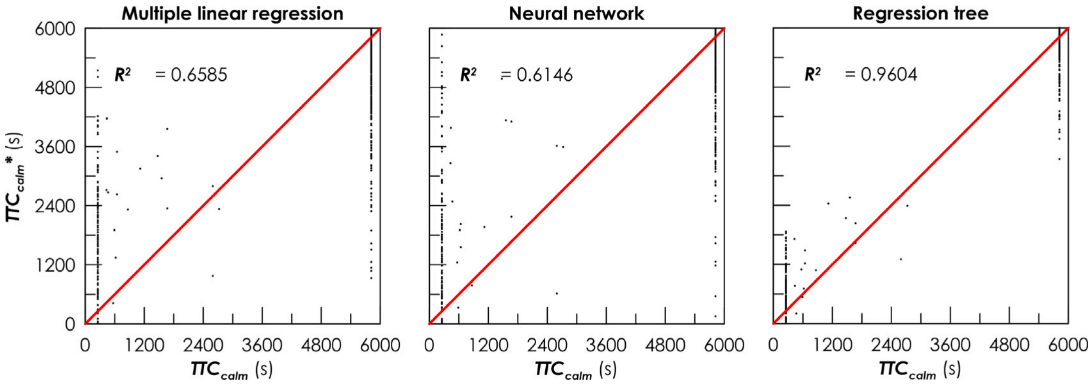

Fig. 15. TTC surrogate models, observed vs predicted values in calm water.

sampling time, for instance, of GPS data, but could be a problem if a higher frame rate is required for the calculation.

The optimal solution is to use the polynomial model or the neural networks, but the application of such models requires the definition of a database with a much higher granularity that those provided in this explorative demonstration study.

6. Conclusions

The paper presents the implementation of the database method for real-time PLL calculation studied in Vassalos et al. (2023) for the operational and emergency framework. Starting with the development of damage databases with dedicated crash analysis and survivability time-domain damage stability calculations, the developed models have been linked to a procedure for the detection of potential collisions for onboard applications. The final scope of the process is the calculation of real-time PLL onboard a passenger ship.

For demonstration purposes, two reference ships have been considered: one cruise ship and one Ro Pax. Four scenarios have been considered per vessel, changing the significant wave height of reference and the dimensions of the striking ships. All the scenarios consider the same path and speeds for the own ship and the target object, to facilitate the comparison between the obtained results. It has to be noticed that such an approximation has been performed to make a first step towards the applicability of this different approach to real time risk estimation to passenger ships. The presented method on the two ship is still not sufficient to grant at 100% the applicability of the methodology onboard of each ship, as PLL and damage analysis are ship specific. Therefore the methodology requires further analysis on a broader set of ship to ensure its applicability onboard. However, this paper is a first step towards reaching such a goal.

As the system is supposed to simulate the instrumentation onboard but no effective data have been at disposal to properly model a virtual interface for the instrumentation, the input to the calculation process has been modified by considering an uncertainty gaussian band. The final live PLL value has been then considered as a multidimensional Quasi-Monte-Carlo QMC Integral resulting from the sampling of different marginal distributions. The process is actually not taking into consideration the possibility for the target ship to make an evasive manoeuvre as the process is monitoring in real time the actual vessel position and heading. However future studies can be performed to include evasive manoeuvre in the path prediction of the target vessel that could lead to the reduction of the estimated PLL.

The application of the process on the 4 reference scenarios for the two passenger ships highlights the potential of the application for onboard purposes, as the procedure results are fast enough to be run in real-time by a conventional laptop, without the need for parallelisation, even though the QMC methods evaluate 1000 individuals for each sample time.

The method presented for real-time PLL estimation introduces a new philosophy for a modern safety assessment for passenger ships. As with any novel method, the first conception of the process is far away to be the definitive robust version of a tool ready for onboard application. However, the first results shown in Vassalos et al. (2023) and Mauro et al. (2023), and the demonstration provided in the present paper are an encouraging step forward towards the effective development of such emergency detection systems for installation on passenger ships. The main weaknesses highlighted through the process concern the dimensions of the datasets used for the generation of damage and survivability databases. Even though the amount of simulation performed was considerable, the opinion is that a larger amount of calculation should be performed, making larger use of filtering techniques for critical case identification (Mauro et al., 2022a) developed in parallel during the FLARE project just marginally applied in the initial development of database creation for survivability.

Another aspect is related to the reliability of crash simulations. The necessity to perform in a short time a relatively large number of calculations imposes the use of simplified methods for the generation of the damaged database. A third consideration should be made on the reproduction of onboard instrumentation, here supposed to ideally work continuously and without errors/failures, just adding a normal standard deviation from an ideal output.

In case it is the intention to pursue this way for the emergency detection onboard passenger ship, the more detailed analysis of the mentioned aspect will for sure enable the development of a unique decision support system for passenger ship emergencies that necessitates the employment of digital technology (like digital twins) to have high fidelity models continuously updating and growing the survivability and damage databases according with the information received from an operating vessel, and constantly providing updated data to the onboard system. Furthermore, the human risk factor is not actually taken into account by the proposed approach as the system is actually conceived to work only with available data, then also the introduction of human factor for the calculation of risk should be taken into consideration.

CRediT authorship contribution statement

Francesco Mauro: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Donald Paterson:** Writing – review & editing, Data curation. **Dracos Vassalos:** Supervision.

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.

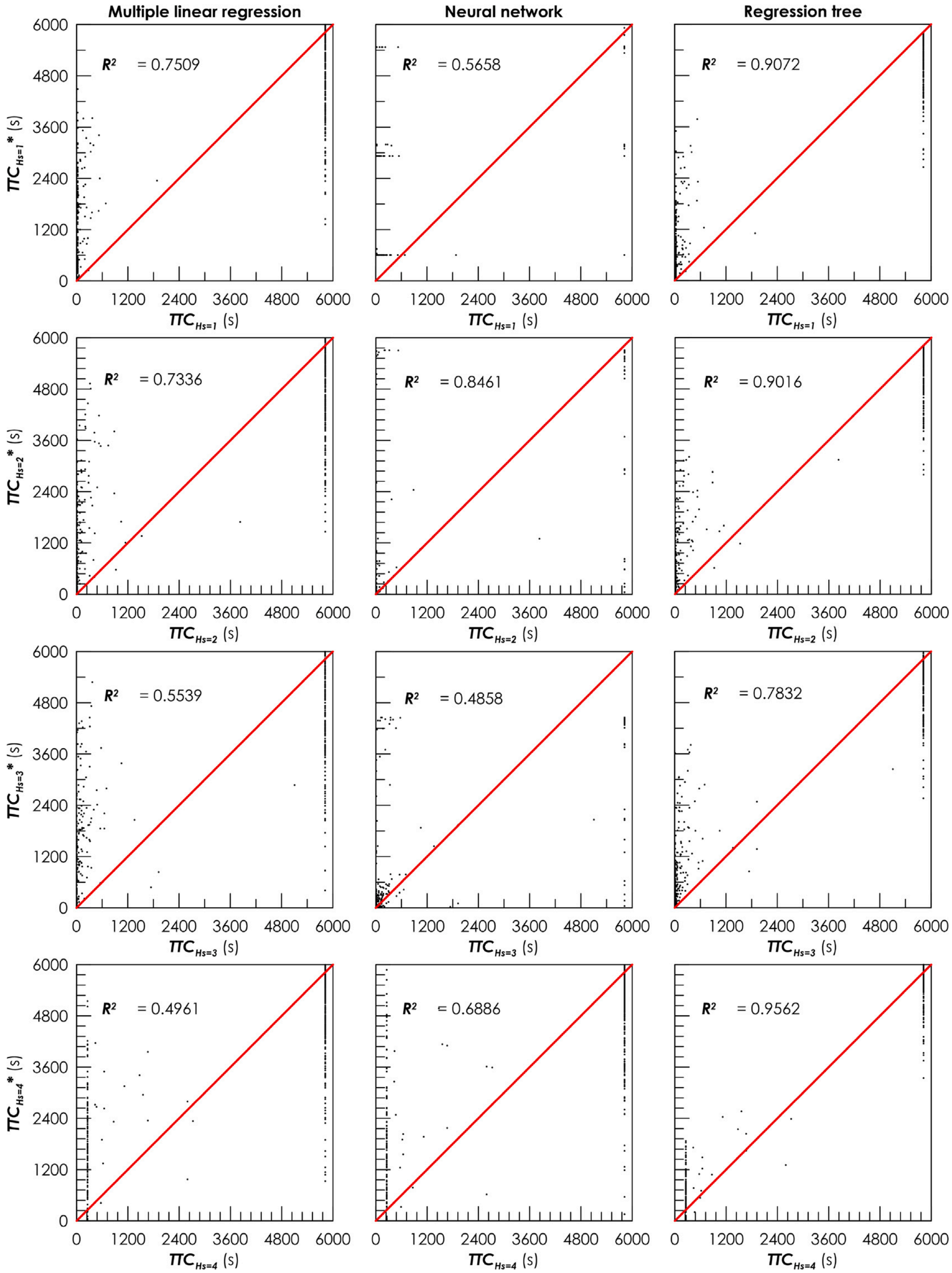

Fig. 16. TTC surrogate models, observed vs predicted values at different wave heights.

Data availability

Data will be made available on request.

Appendix A. Surrogate models for the reference cruise ship

The appendix reports the surrogate models generated for the reference cruise ship described in Section 4.1. Damage database derives from direct calculations with software SHARP, while survivability database derives from direct flooding simulations with the software PROTEUS3. Surrogate models are determined according to three different strategies, multiple linear regressions, neural networks and forest trees.

A.1. Damage surrogate model

Considering all the 11 striking ships described in Mauro et al. (2023) for a unique surrogate model implies the adoption of additional dependent variables to describe the different vessels. Here, besides the dependent variables described in the previous sections (thus the

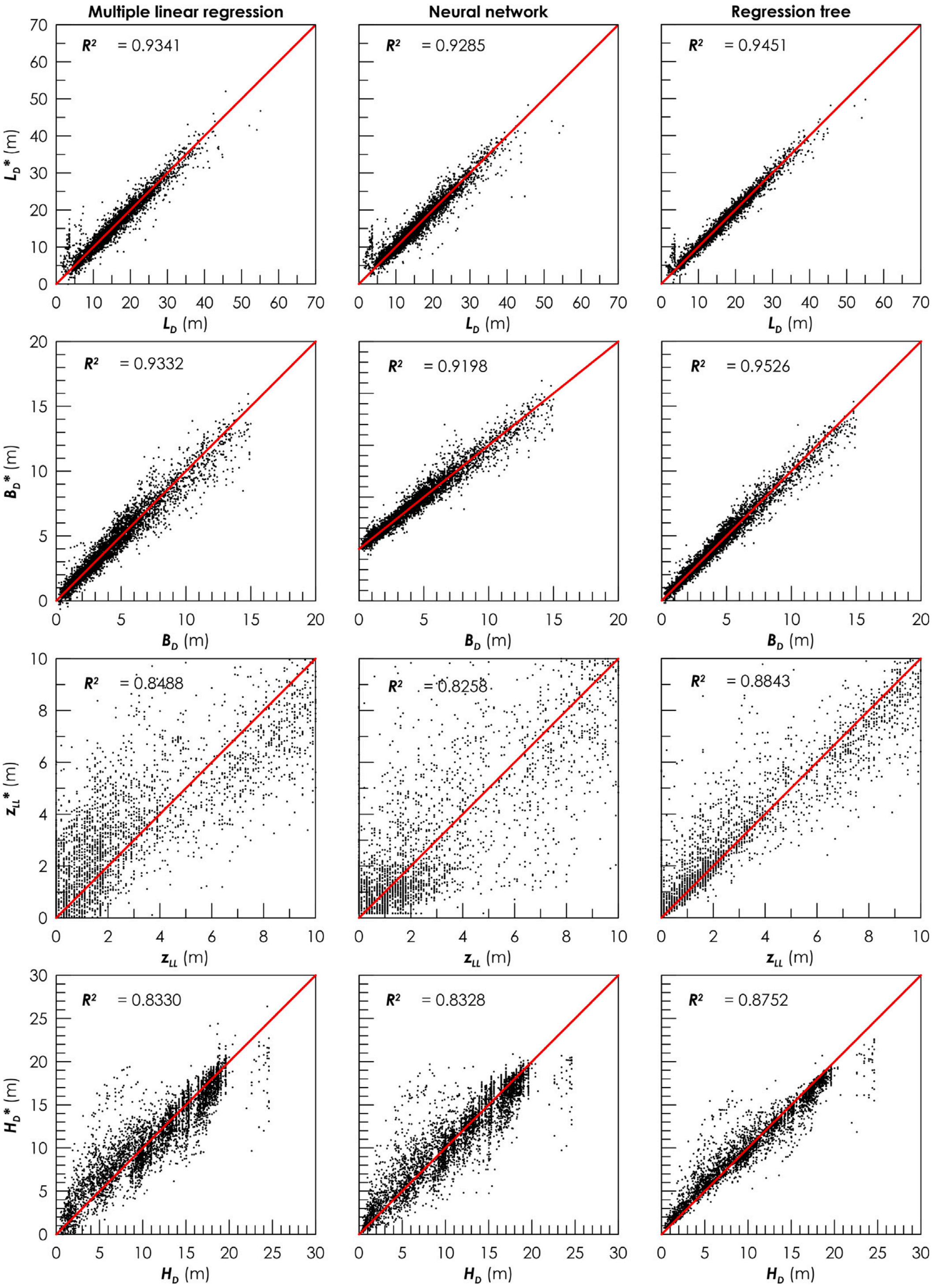

Fig. 17. Damage dimensions surrogate models, observed vs predicted values.

input of SHARP simulations), ships are identified using three additional dependent variables describing the ship length L_s, the ship breadth B and the maximum draught T_{max}, such quantities being available from AIS data.

The same methods to generate surrogate models have been employed in this new subset of observations, introducing the new mentioned parameters in the set of dependent variables. The results highlight that the general behaviour of these global surrogate models is better than the ship specific cases concerning the average values of R^2. The multiple linear regression models show correlation coefficients above 0.6 for all the damage dimensions, with values above 0.84 for length and penetration. Neural networks have comparable performances with the previous simpler model. Therefore, it is probable that the number of observations used is still not large enough to benefit the regressions capability of the network. Forest tree has the highest R^2 for all the damage dimensions, providing satisfactory results also for H_D.

The comparison between observed and predicted damage dimensions Is given in Fig. 14. Here it can be observed that the dimension

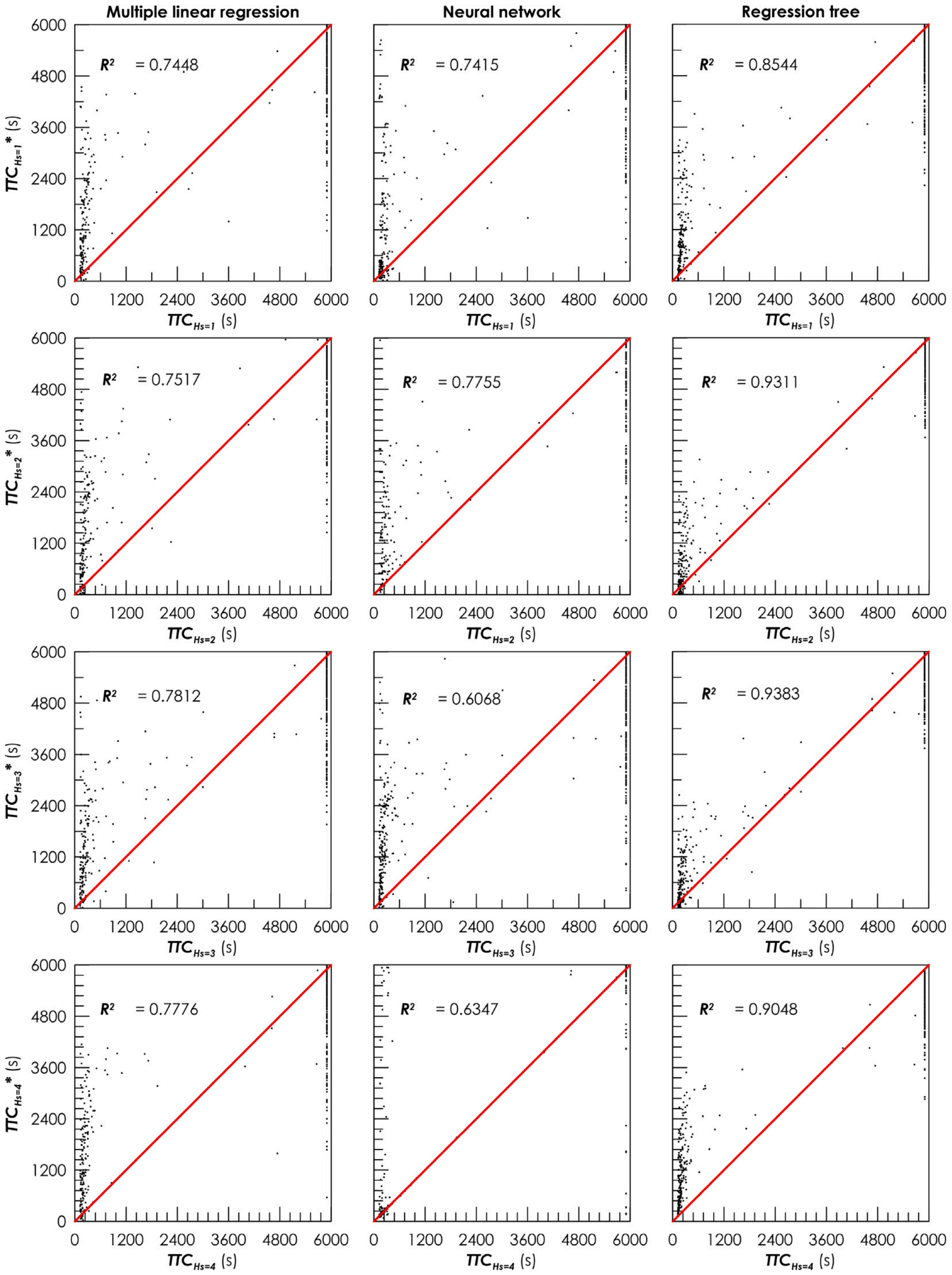

Fig. 18. TTC surrogate models, observed vs predicted values at different wave heights.

has more problems to be reproduced by all models in H_D. Once again, the reason should be searched in the modelling of damage provided as input to the fitting procedure.

Considering the uncertainties of the methods used to generate the damage dimensions from the direct calculations, it is advisable to consider the multiple linear regression model as a valid starting point for the embryonic development of an onboard risk assessment tool. Once more detailed inputs are introduced into the database, the adoption of surrogate models derived from forest trees is for sure advisable. Neural networks require the presence of a larger amount of data to be more effective than other presented models.

A.2. Survivability surrogate models

The proposed analysis to generate a vulnerability database follows the steps already described in Section 3. The process is preferably applicable for calm water, thus performing the initial study discarding the presence of waves. The initial calculations can also consider a given significant wave height, showing the influence of irregular waves in a reference sea state on the initial sample. However, the simulation of irregular waves increases the computation time and introduces additional randomness to the process. For this study, a maximum simulation time of 90 min has been used.

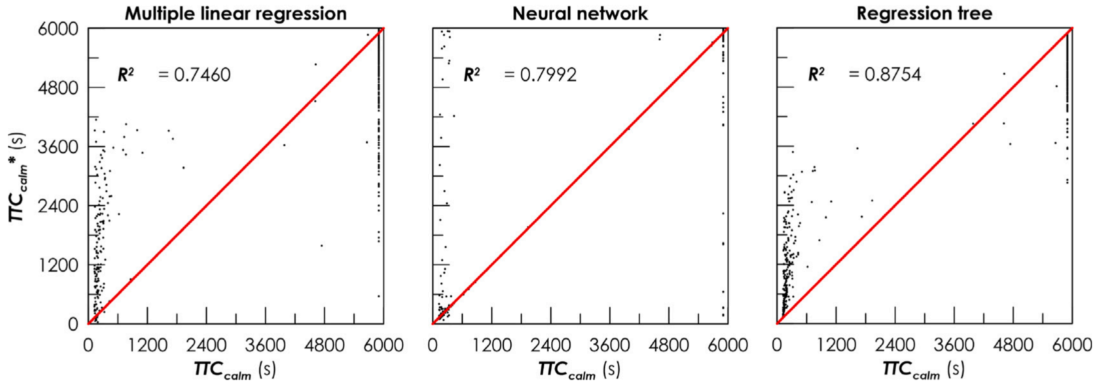

Fig. 19. TTC surrogate models, observed vs predicted values in calm water.

By performing dynamic simulations on this set of damages, it is possible to identify the critical cases of this reduced group of scenarios. Besides true capsizes (simulations where the vessel heeling exceeds 90 degrees or where the ship sinks within the maximum simulation time), alternative criteria allow for detecting critical damage scenarios (Mauro et al., 2022a,b).

With this strategy, 500 simulations have been performed in calm water and with significant wave heights of 1,2,3 and 4 metres in order to have the initial database for the surrogate model detection. The reported case shows the problem of the stochastic nature of the irregular waves. As the use of wave spectra with constant amplitude and random phases generate different behaviour of the damaged ship with consequent detection of multiple time to capsize, 10 repetition have been performed for each case in irregular waves. This is not necessary for calm water. Therefore, a total number of 20,000 simulations has been used for the irregular wave case and 500 for the calm water. The simulation time has been set to 90 min for all the simulated scenarios.

The same techniques and methods employed for the damage dimension surrogate models have been applied here for the vulnerability of the ship. For the case of vulnerability, the dependent and independent variables are different from the case of the damage breach surrogate model. The independent variable for survivability is the time to capsize, TTC, expressed in seconds. Such a choice is necessary for the determination of the potential loss of lives PLL with a Level 2-1 approach, and it has been evaluated for calm water and 4 different wave heights. The dependent variables for this problem are the outputs of the damage dimension surrogate model (L_D, B_D, z_{LL} and H_D) plus the location of the damage x_D.

The same general remarks given on the performance of the training methods apply also here, with the forest tree method performing better than the other two, considering all the tested environmental conditions. However, the goodness of fit represented by the R^2 coefficient is not always giving the real effective matching between predicted and observed data. For this specific case of the TTC, this is effectively 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. Fig. 15 shows the TTC comparisons in calm water and Fig. 16 in waves.

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 s. 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. The spread of values along the extremities is reduced only by the forest tree models but is still present.

However, considering as a main issue the detection of a capsize case in stead of the determination of the exact TTC, it should be noted that all the regression tree models underestimate the TTC of the 10% of safe cases but are detecting all the capsize cases. Thus, the model based on the tree forest is the most suitable for the scope of a real time risk assessment. In fact, the resulting PLL calculated with a Level 2-1 approach will be higher than the observed value.

It should be stressed that the study has been performed to explore a different approach to the real time risk estimation. Therefore, further investigation should be performed in the future to improve the methodology and give sufficient reliability to the method for an effective onboard application. In fact the estimation of PLL is ship specific and the demonstration provided on only two types of reference ship is just a first step towards the application of the methods to passenger ship in general.

Appendix B. Surrogate models for the reference Ro Pax

The appendix reports the surrogate models generated for the reference Ro Pax described in Section 4.1. Damage and survivability databases and associated surrogate models are derived with the same methods described in Appendix A.

B.1. Damage surrogate model

The same methods to generate surrogate models described in Mauro et al. (2023) have been employed in this new subset of observations, introducing the new mentioned parameters in the set of dependent variables. The results highlight the average values of R^2 are quite high. The multiple linear regression models show correlation coefficients above 0.8 for all the damage dimensions, with values above 0.9 for length and penetration. Neural networks have comparable performances with the previous simpler model. Therefore, it is probable that the number of observations used is still not large enough to benefit the regressions capability of the network. Forest tree has the highest R^2 for all the damage dimensions, providing satisfactory results also for H_D.

The comparison between observed and predicted damage dimensions is given in Fig. 17 . Here it can be observed that the dimension has more problems to be reproduced by all models in H_D. Once again the reason should be searched in the modelling of damage provided as input to the fitting procedure.

B.2. Survivability surrogate models

The same techniques and methods employed for the damage dimension surrogate models have been applied to the vulnerability of the Ro Pax, by employing the same strategy and variables used for the cruise vessel in Appendix A.

The same general remarks given in Mauro et al. (2023) on the performance of the training methods apply also here, with the forest tree method performing better than the other two, considering all the tested environmental conditions. However, the goodness of fit represented by the R^2 coefficient is not always giving the real effective matching between predicted and observed data. For this specific case of the TTC, this is effectively 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. Fig. 18 shows the TTC comparisons in waves and Fig. 19 in calm water.

It can be observed that the predicted and observed values are dense close to the extremities of the TTC space, having a higher density closer to TTC=0 s. 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. The spread of values along the extremities is reduced only by the forest tree models but is still present.

However, considering the main issue of the detection of a capsized case instead of the determination of the exact TTC, it should be noted that all the regression tree models underestimate the TTC of the 10% of safe cases but are detecting all the capsized cases. Thus, the model based on the tree forest is the most suitable for the scope of a real-time risk assessment. The resulting PLL calculated with a Level 2-1 approach will be higher than the observed value.

It should be stressed that the study has been performed to explore a completely novel approach to real-time risk estimation. Therefore, further investigation should be performed in the future to improve the methodology and give sufficient reliability to the method for an effective onboard application. The indications found for the Ro Pax case are in line with the considerations reported in the previous section for the reference cruise ship case.

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