Evacuation analysis of open deck areas on passenger ships

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Abstract. Passenger ships evacuation analysis is nowadays a required step in the ship design process. In this sense, a new set of international Regulations has been issued to improve the survival ability of passenger and ro-ro ships. The “Safe Return to Port” Regulation is referring to the need to grant adequate ship functionality when a casualty occurs (e.g. fire or flooding), requiring the ship evacuation when damage exceeds a given threshold. For such a reason, the evacuation analysis is mandatory for both new and existing passenger and ro-ro ships, since the early stages of design. The International Maritime Organisation Guidelines prescribe the examination of additional scenarios besides the standard ones. The present work presents a case study for the evacuation of a 4906-person cruise ship, considering the specific example of the open deck, which is one of the additional scenarios required by regulations. The advanced calculation method has been used to simulate the evacuation process, using software EVI.

Keywords. Evacuation analysis, Ship safety, Passenger ship, Open deck areas, Safe return to port

1. Introduction

The topic of passenger evacuation is a relevant issue for naval designers since the International Maritime Organisation (IMO) regulate this topic with the Convention for the Safety of Life at Sea (SOLAS). Regulation [1] knew as ”Safe Return to Port” states that a ship should be able to sail back to port, if a specific casualty threshold, defined in the case of fire or flooding, is not exceeded. In this case, the passenger and part of the crew should reach the so-called Safe Areas. In the case of casualty threshold exceedance, it is necessary to evacuate persons towards the safe areas within 3 hours and abandon the ship with lifeboats. In both cases, an evacuation analysis has to be performed to identify possible congestion points along the escape route to the Safe Areas and to evaluate the total evacuation time. From 1999 to 2007, the IMO Maritime Safety Committee (MSC) issued three Circulars [2,3,4,5] describing the guidelines to perform an evacuation analysis of a passenger ship. The first three documents [2,3,4] were referring to a

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simplified calculation method that evaluates the flow of persons with the hydraulic similarity. With the continuous growth of the passenger ship dimensions and consequently with the transport of a large number of people (both passengers and crew), the simplified method could be not accurate enough to simulate the evacuation of the ship. In this sense, advanced calculation methods have been studied [6,7] to improve the capability to detect congestion areas and evaluate the total evacuation time. The fourth circular [5] adds these enhanced methods as a possibility to perform the evacuation analysis. Because of that, considerable effort has been given to develop computer simulation software. Nowadays several specialised tools are present for the evacuation of passenger ships (e.g. *maritime*EXODUS [8], AENEAS [9,10], EVI [11,12], IMEX [13] and VELOS [14]), compared and validated on benchmark cases [15]. Based on a collection of evacuation data for passenger vessels [16], IMO issued in 2016 a new Circular [17], introducing new simulation cases to the previous regulation.

The present article is aimed to investigate one of the new cases introduced by the most recent regulation, i.e. the open deck case. Previous authors works [18,19] and others [20,21,22] did not consider the new scenario. Here, for a cruise ship, the Main Vertical Zone (MVZ) in which an open area is present has been modelled inside the EVI environment to estimate the evacuation time and the detection of possible congestion areas.

2. Evacuation analysis regulation and modelling

The Regulation in force [17] is giving a guide for the implementation of amendments to SOLAS regulation [23], making evacuation analysis mandatory for all the passenger ships constructed on or after 1 January 2020. The present document allows the use of a simplified or an advanced method to perform the analysis. The simplified method assumptions are limiting. However, the simplified procedure can provide an estimate of the expected evacuation performance during early design iterations of the ship. Once the level of detail of the general arrangement of the passenger ship is high, and the complexity of the geometry increases, then the advanced method is recommended and preferred.

2.1. Regulation

The objective of the guidelines is to assess the evacuation process through a set of benchmark cases (mainly based on analysis of fire risk), not necessarily representative of a real emergency. The data and parameters given in the guidelines refer to civil building experience. Thus the interim guidelines will be continuously developed according to ongoing research results. For such a reason, the simulation of the benchmark cases should be aimed to identify inadequate escape arrangements and possible congestion points, optimising the evacuation arrangement and consequently enhancing safety.

The compliance of benchmark cases is checked with the following standards:

$$t_{TOT} = 1.25\,(R+T) + \frac{2}{3}\,(E+L) \leq n \tag{1}$$

$$E+L \leq 30 \text{ min} \tag{2}$$

where t_{TOT} is the total evacuation duration, R is the response duration, T is the total travel duration and $E+L$ is the embarkation and launching duration. Parameter n has to be set to 60 minutes for ro-ro ships and passenger ships with at most 3 MVZ or 80 minutes for passenger ships with more than 3 MVZ.

The benchmark scenarios should be as a minimum four, divided between *day* and *night* cases. The crew distribution should be compliant with Chapter 13 of the International Code of Fire Safety Systems (FSS Code), which is:

- *night scenario*: all passengers in cabins with maximum berthing capacity fully occupied. 2/3 of the crew members in their cabins and the remaining 1/3 distributed as follows:
  · 50% located in the service spaces;
  · 25% located at the emergency stations;
  · 25% initially located at the assembly stations, successively they should proceed towards the most distant passenger cabin assigned to that assembly station, in counter flow with the evacuees. Once the assigned cabin is reached, these crew members are no more considered in the simulation.
- *day scenario*: passengers in public spaces occupy 3/4 of the maximum capacity. 1/3 of the crew members in their accommodation spaces. 1/3 of the crew in the members in the public spaces and the remaining 1/3 distributed as follows:
  · 50% located in the service spaces;
  · 25% located at their emergency duty locations;
  · 25% initially located at the assembly stations, successively they should proceed towards the most distant passenger cabin assigned to that assembly station, in counter flow with the evacuees. Once the assigned cabin is reached, these crew members are no more considered in the simulation.

In case more detailed and realistic data on the crew distribution are available, they can be used to improve the simulation. The evacuation cases to simulate should be the following ones:

- *case 1* (primary evacuation case, night): the persons are distributed according to *night scenario*. The simulation is performed on the whole ship and passenger and crew evacuate via the main escape routes towards the assigned assembly stations;
- *case 2* (primary evacuation case, day): the persons are distributed according to *day scenario*. Evacuation is performed as per *case 1*;
- *case 3* (secondary evacuation case, night): the persons are distributed according to *night scenario*. Only the MVZ, which generates the longest individual assembly duration, is further analysed according to one of the following alternatives (alternative 1 is preferred for ro-ro ships):
  · *Alternative 1*: one complete run of the stairways having largest capacity is considered unavailable;
  · *Alternative 2*: 50% of the persons of the most populated adjacent MVZ is forced to move into the considered MVZ and proceed to the relevant assembly station;
- *case 4* (secondary evacuation case, day): the persons are distributed according to *day scenario*. Evacuation is performed as per *case 3*;

One of the novelties of the current regulation consists of the introduction of two optional scenarios. They can be considered when relevant compared to standard ones. Additional cases are:

- *case 5* (Open deck, day): in case an open deck with a gross surface area larger than 400 m^2 or capable to accommodate more than 200 persons is present onboard, then this additional day case should be analysed. The initial population of *case 2* should be modified considering the open deck as an additional public space with an initial density of 0.5 person/m^2;
- *case 6* (Embarkation): in case embarkation and assembly stations are not coincident, an analysis of the travel duration from the assembly station to the entry point of the lifeboats should be taken into account to determine $E+L$. All the persons the ship is certified to carry are initially distributed in the assembly stations, according to their capacities. Possible congestions directly in front of the lifeboats entry point should be considered in the simulation.

In case the total number of persons calculated as per the above cases exceeds the maximum number of persons the ship is certified to carry, the initial distribution of people should be scaled to respect the given constraint.

In case the total evacuation time t_{TOT} evaluated with equation (1) exceeds the limits in one of the analysed cases, or equation (2) is not satisfied for embarkation procedures, corrective actions should be considered at the design stage, modifying the arrangements affecting the evacuation system. For existing ships, the evacuation procedures should be reviewed to avoid the detected congestion points.

2.2. *Advanced modelling techniques*

The advanced evacuation method can be carried out with IMO certified software. Nowadays the state-of-the-art on the evacuation of large passenger ships is provided by complex computer-based simulation models. They can represent the detailed internal layout of the vessel, considering the interactions between persons and the ship's arrangement.

A possible modelling technique grants that, at each instant of the simulation, a force-based system (Social Force approach) determines the behaviour of all persons, according to the distance between an agent and an obstacle. Other methods simplify the problem dividing the space into grids (Cellular Automata Models, CAM). Between them, the most used is the Agent-Based Model (ABM). The ABM technique simulates the interaction between the agents for the evaluation of the impacts on the ambient as a whole. Other methods can be used to model the evacuation process, as the Lattice Gas Modelling, the Fluid-dynamics models or the Game Theoretical Modelling. In this work, the EVI simulation tools is used to evaluate the total evacuation time. EVI adopts an ABM technique where each passenger and crew member is corresponds to an individual agent with unique characteristics and behaviours. Moreover, EVI uses a *hybrid* approach with a multi-level structure, combining macroscopic and microscopic models. The first model class describes the evacuation flow rate as per Annex 2 of regulation [17], while the second one implements the human behaviours models.

Inside EVI, the path planning process is of primary importance because of the extreme complexity of the cruise vessel internal layout. Each agent has a specific location at each instant. EVI calculates the distance between the agent and all the targets (doors,

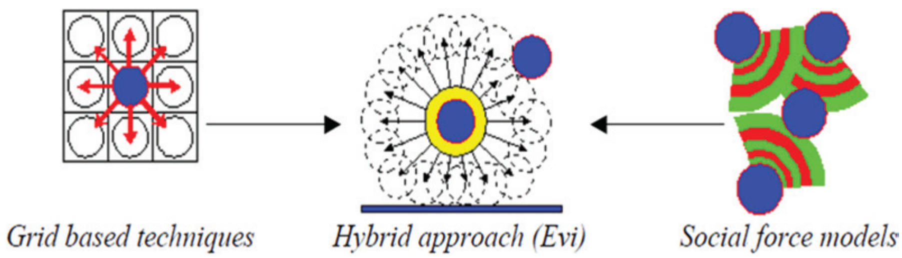

Figure 1. Hybrid modelling technique in EVI [6]

stairs or assembly zones) of the space so that the agent ca choose the shortest route (evaluated with Dijkstra algorithm). In such a way, EVI combines social forces and grid-based techniques (see Figure 1), allowing the agent to decide the direction of movement according to the presence of other individuals and obstacles. This calculation structure is named *mesoscopic* approach.

3. Case test

The case test is representative of a 18-deck passenger cruise ship. The vessel has an open deck with a gross surface area larger than 400 m^2. Thus, it is a perfect candidate to perform an evacuation simulation as per *case 5* scenario. Such a kind of simulation requires the modelling of the entire ship. However, for confidentiality reasons, only the MVZ geometry, including the open deck, is at disposal for the analysis. In this sense, the proposed test case is representative of a *case 4* scenario with a modified initial population according to open deck new settings.

3.1. Geometry modelling

Before starting the evacuation analysis, it is mandatory to load the pedestrian geometry of the ship inside EVI. The software allows drawing the ship layout starting from *dxf* files per each deck. In such a way, it is possible to reproduce the internal spaces in conformity with the real arrangement of the ship. Each area is connected to the others with doors and assigned to the reference main escape route used in the macroscopic model. It is possible to define the type of local (passenger room, crew room, open space, crew service room, etc.), the maximum capability and other parameters necessary to set the microscopic model. Stairs and assembly stations have to be modelled inside the program to determine the correct flow for the macroscopic model. In Figure 2, the equivalence between general arrangement and EVI geometry is presented for the reference ship, showing a passenger cabin deck and a crew cabin deck. As already mentioned, the cruise ship holds 18 decks in the analysed MVZ, including different classes of spaces. In this case, the MVZ includes two public zones (a theatre and an open deck) and both crew and passenger cabins. Table 1 shows the space typologies per each deck. In particular (see Table 1) decks 6 and 7 hold the theatre, while 17, 18 and 19 are the open deck. Deck 7 includes also the two assembly stations, one is on the starboard side and the other to the port side (see Figure 3), so that two main evacuation flows can be defined pointing to each station. All the agents located on the port side will aim to the port assembly station

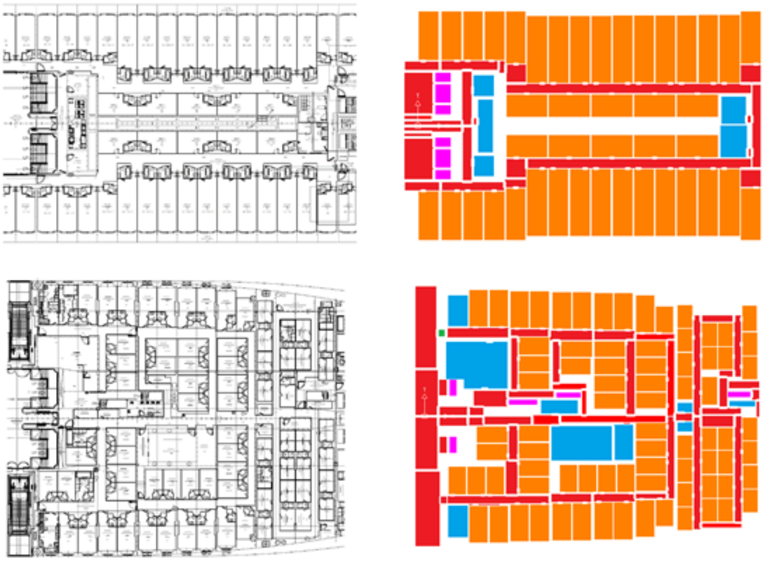

Figure 2. General arrangement and EVI model for a passenger cabin deck (*top*) and a crew cabin deck (*bottom*)

Table 1. Typologies of areas in the modelled MVZ

	Types				
	crew cabins	passenger cabins	service rooms	public spaces	assembly station
Deck 1	-	-	X	-	-
Deck 2	-	-	X	-	-
Deck 3	X	-	-	-	-
Deck 4	X	-	-	X	-
Deck 5	X	-	-	-	-
Deck 6	-	-	-	X	-
Deck 7	-	-	-	X	X
Deck 8	X	X	-	-	-
Deck 9	X	X	-	-	-
Deck 10	-	X	-	-	-
Deck 11	-	X	-	-	-
Deck 12	-	X	-	-	-
Deck 14	-	X	-	-	-
Deck 15	-	X	-	-	-
Deck 16	-	X	-	-	-
Deck 17	-	-	-	X	-
Deck 18	-	-	-	X	-
Deck 19	-	-	-	X	-

and the opposite for the starboard side. Only in the open areas, this is not possible, and each agent will point to the closest exit of the zone and then will follow the flow path associated with that door. From the 2D drawings it is then possible to obtain the final 3D ambient (Figure 4) used for the evacuation simulation.

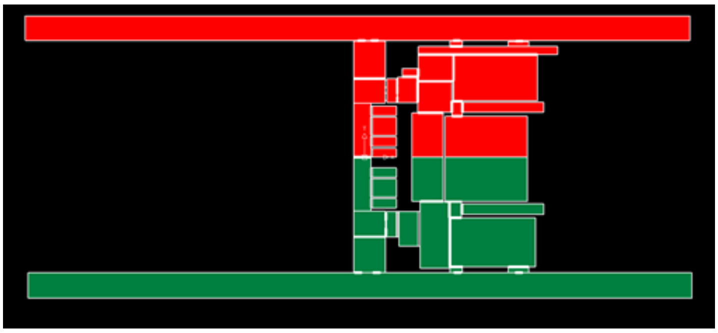

Figure 3. Port side (*red*) and starboard side (*green*) assembly stations at deck 7

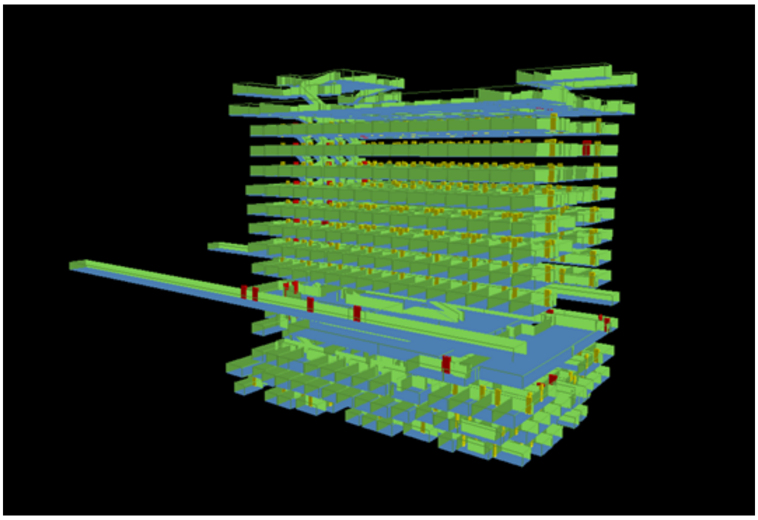

Figure 4. 3D model of the analysed MVZ for the evacuation simulation

3.2. Initial conditions

The considered evacuation scenario is a modified version of *case 5* described in the regulation [17]. The analysed MVZ contains 1331 persons divided into 922 passengers and 409 crew members. Even though the simulation is not compliant with a benchmark case, the input parameters needed to set up the calculation are according to the recommendations for an open deck scenario. In the specific, the distribution of passenger and crew respects the indications of *case 5*. The passengers occupy 3/4 of public spaces maximum capacity, considering a density of 0.5 persons/m^2 for the open deck. The passenger population reflects the parameters specified by the regulation regarding the gender, the age and the associated reaction time and average walking speed. The same is for the crew. For the passenger and crew age and average-speed, a uniform distribution between the range limits has been used to generate the population. The reaction time reflects a truncated logarithmic-normal distribution up to 300 seconds. Figure 5 shows the initial population for the analysed MVZ, highlighting the presence of the passengers in the public areas, especially on the open deck. The selected case is worthy of investigation, because,

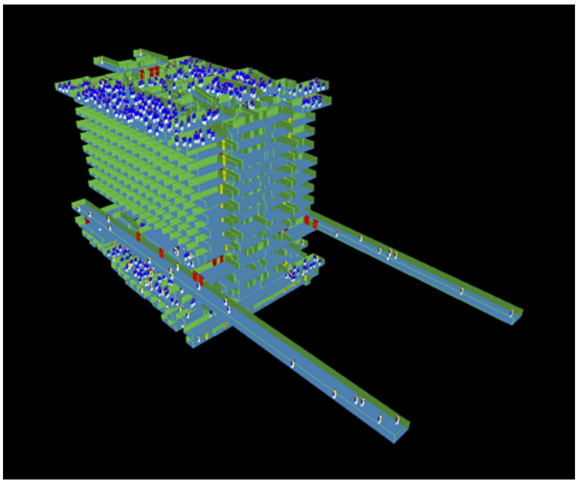

Figure 5. Initial population overview in EVI 3D environment

due to the high number of passenger on the open deck, it can be a source of possible congestions on the main escape routes. So it can be considered as a critic case for the evacuation of the analysed cruise ship.

4. Results and discussion

The evaluation of the evacuation time for the selected test case should be compliant with the regulations. Since the initial position of the agents and the associated characteristics is stochastic, a single simulation is not sufficient to evaluate the evacuation time. Multiple calculations have to be performed to estimate an evacuation time value corresponding to sufficiently high percentile of the simulations. In EVI, it is possible to execute a batch running of 50 simulations of the same scenario, which is considered, according to the software developers, a sufficient number of simulation to estimate evacuation time. While analysing the simulation results, the final evacuation time value corresponds to the 0.95 probability of empirical cumulative density function (ECDF) of the calculated times. The software is evaluating the $R+T$, means the sum of the reaction and the travel time of the agents. The simulation stops once the last agent reaches the assigned target. Here, the evacuation time does not include the additional crew duties. In fact, for the selected MVZ, the cabins are closer to the assembly stations than the open deck. So, the counterflow of few agents will not affect too much the total evacuation time.

The total evacuation time t_{TOT} is determined by estimating $R+T$ with the ECDF and then using equation (1). Figure 6 represents the ECDF obtained from the 50 simulations with the resulting $R+T$ of 739.75 seconds. Then, applying equation (1), the t_{TOT} is 35 minutes and 15 seconds, considering an $E+L$ of 30 minutes (as the upper limit of equation (2) to be on the safety side). Having the vessel more than 3 MVZ, then the value has to be compared with n=80 minutes, so the performance standards are satisfied.

Besides the total evacuation time determination, the evacuation analysis is giving other information, as, for example, the presence of possible congestion areas. The software reports the five most critical locations for congestions according to the flow rates

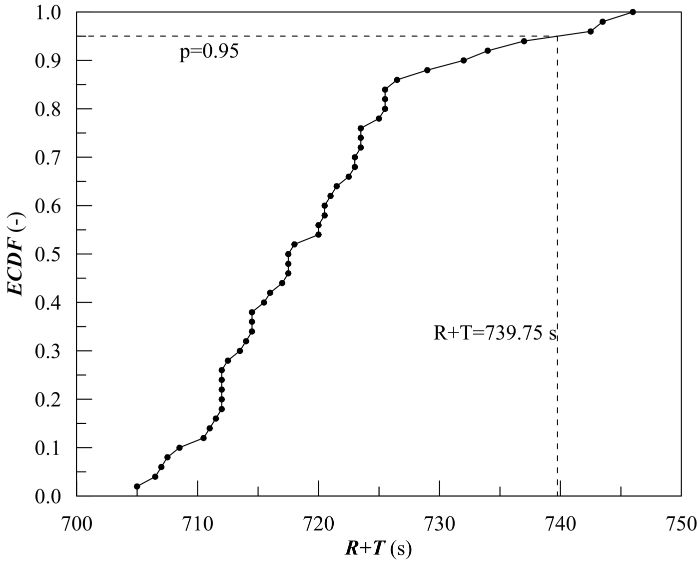

Figure 6. Empirical cumulative density function (ECDF) of $R+T$

and agent density, counting the number of congested agents. In the present simulations, the software did not recognise any critical area, while highlighting that the zones close to the assembly stations are the one in which the final flow rate and the density are the highest. However, no one of the calculated values exceeds the standard thresholds. Moreover, the software gives an individual statistic per each assembly station, in such a way to detect whether one of the possible main escape routes presents a criticality. For the present case, the two assembly stations have comparable performances, with a difference inside the 6 seconds on the 0.95 ECDF value for $R+T$.

5. Conclusions

In the present work, an evacuation analysis has been performed to calculate the total evacuation time for a cruise ship having an open deck. This case is worthy of investigation since it is representative of one of the additional scenarios introduced by the regulation in force for passenger ships evacuation. On this purpose, the main aspects and issues of the new guidelines have been accurately described to underline the importance to execute evacuation analysis during the design process of a passenger ship.

The evacuation analysis has been performed with an advanced method on a single MVZ with an open deck using software EVI. The software allows loading the real geometry of the internal layout to execute a realistic pedestrian model of the ship. The simulation results highlight that no congestion points are present in the escape routes and that the total evacuation time of the MVZ satisfies the required time performances. This study is an explorative attempt to evaluate the possible complication for evacuation given by a high person density in public area such as an open deck. In the present case, no critical issues have been highlighted. However, further studies are needed to investigate the behaviour of the evacuation of open areas with respect to the whole ship.

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References

[1] SOLAS, Regulation II-2/21-26, Convention for the Safety of Life at Sea, 2006.

[2] IMO, Interim guidelines for a simplified evacuation analysis on ro-ro passenger ship, *MSC/Circ. 909*, International Maritime Organisation, 1999.

[3] IMO, Interim guidelines for a simplified evacuation analysis of high-speed passenger crafts, *MSC/Circ. 1001*, International Maritime Organisation, 2001.

[4] IMO, Guidelines for a simplified evacuation analysis for new and existing passenger ship, *MSC/Circ. 1033*, International Maritime Organisation, 2003.

[5] IMO, Guidelines for evacuation analysis for new and existing passenger ship, *MSC/Circ. 1238*, International Maritime Organisation, 2007.

[6] D. Vassalos, L. Guarin, G.C. Vassalos, M. Bole, H.S. Kim, J. Majumder, Advanced evacuation analysis-Testing the ground on ship, *Second International Conference in Pedestrian and Evacuation Dynamics*, London, 2003.

[7] A. Lopez Pineiro, F. Perez Arribas, R. Donoso, R. Torres, Simulation of passengers movement on ship emergencies. Tools for IMO regulations fulfilment. *Journal of Maritime Research* **II**(1) (2005), 105–125.

[8] S. Gwynne, E.R. Galea, C. Lyster et al.,Analysing the Evacuation Procedures Employed on a Thames Passenger Boat Using the *maritime*EXODUS Evacuation Model, *Fire technology* **39**(3) (2003), 225–246.

[9] T. Meyer-König, H. Klüpfel, M. Schreckenberg, Assessment and analysis of evacuation processes on passenger ships by microscopic simulation, *Schreckenberg and Sharma [2]* (2002), 297–302.

[10] T. Meyer-König, P. Valanto, D. Povel, Implementing Ship Motions in AENEAS - Model Development and First Results, *Pedestrian and Evacuation Dynamics*, 2005.

[11] G. Vassalos, *Design for Ease of Passenger Evacuation in a Ship-Sea Environment*, Master of Philosophy, Universities of Glasgow and Strathclyde, 2005.

[12] C. Azzi, A. Pennycott, G. Mermiris et al., Evacuation Simulation of Shipboard Fire Scenarios, *Fire and Evacuation Modelling Technical Conference*, Baltimore, 2011.

[13] J.H. Park, D.K. Lee, H.T. Kim et al., Development of evacuation model for human safety in marine casualty, *Ocean Engineering* **31**(11) (2004), 1537–1547.

[14] A.I. Ginnis, K.V. Kostas, C.G. Politis et al., VELOS: A VR platform for ship-evacuation analysis, *Computer-Aided Design* **42**(11) (2010), 1045–1058.

[15] E.R. Galea, R.C. Brown, I. Filippidis et al., Collection of Evacuation Data for Large Passenger Vessel at Sea, *Pedestrian and Evacuation Dynamics*, 2011.

[16] R. Brown, E.R. Galea, S. Deere, L. Filippidis, IMO Inf. paper summary - Response time data for large passenger ferries and cruise ship, *Safeguard Passenger Evacuation Seminar*, London, 2012.

[17] IMO, Revised guidelines on the evacuation analysis for passenger ships, *MSC/Circ. 1533*, International Maritime Organisation, 2016.

[18] V. Bucci, A. Marinò, G. Trincas, G. Zanutto, Innovative tools for advanced evacuation analysis of passenger ships, *18th International Conference on Ships and Shipping Research NAV 2015*, Lecco, 2015.

[19] V. Bucci, A. Marinò, F. Mauro, R. Nabergoj, C. Nasso, On Advanced Ship Evacuation Analysis, *22nd International Conference on Engineering Mechanics*, Svratka, 2016.

[20] I. Gypa, E. Boulougouris, D. Vassalos, Decision support tool for modelling security scenarios onboard passenger ships, *Maritime Transportation and Harvesting of Sea Resources*, 2017.

[21] I. Gypa, E. Boulougouris, D. Vassalos, Quantification of the maritime security problem onboard passenger ship, *7th Transport Research Arena TRA 2018*, Vienna, Austria, 2018.

[22] D. Vassalos, L. Guarin, M. Bole, J. Majumder et al., Effectiveness of passenger evacuation performance for design , operation & training using first-principles simulation tools, 2019.

[23] SOLAS, Regulation II-2/13.3.2.7, Convention for the Safety of Life at Sea, 2016.