22nd International Conference
ENGINEERING MECHANICS 2016
Svratka, Czech Republic, 9 – 12 May 2016

ON ADVANCED SHIP EVACUATION ANALYSIS

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Abstract: *New cruise passenger ships are trending towards "gigantism", consequently together with size also the number of passengers and crew increases. For this reason, international regulations known as "Safe Return to Port" are more and more aimed at upgrading intrinsic ship safety in event of fire or flooding. When the accident exceeds a fixed threshold, a ship safe evacuation must be guaranteed. To this end evacuation analysis becomes a primary task in passenger ship design, since the early stages. According to IMO Regulations, evacuation analysis can be tackled in two different ways: a simplified method or an advanced one. The latter involves the use of specific certified computational tools. In this work an advanced evacuation analysis for a cruise passenger ship with about 3600 persons on board is presented.*

Keywords: Safe Return to Port, Ship Evacuation Analysis, Ship Safety.

1. Introduction

In the last years, the construction of new cruise passenger ships reported even larger ships carrying thousands of persons (both passengers and crew). For such ships the survivability in event of fire or flooding has become of paramount importance. The matter is regulated through the International Convention for the Safety of Life at Sea (SOLAS). In particular Regulations II-2/21-23 known as *Safe Return to Port* state that the ship should be able to return to port if the specified casualty threshold, properly defined in event of fire or flooding, is not exceeded. In such a case the persons involved should be moved towards the so-called Safe Areas. If instead the casualty threshold is exceeded, it is necessary within 3 hours to evacuate persons towards the Safe Areas and then abandon the ship with the survival crafts. In both cases, the evacuation analysis must be performed in order to check the effective time necessary to gather persons in the Safe Areas, putting in evidence possible congestion points along the escape routes.

This paper presents the results of a study carried out with a simulation tool (AENEAS) within a wider research program oriented to check the capability of different certified software to simulate consistently the evacuation of new cruise passengers ships.

2. Regulations

Until now, the evacuation analysis is mandatory, in the simplified form, only for ro-ro passenger ships, while the new requirements (IMO Circular MSC.1/Circ.1238 "Guidelines for evacuation analysis for new and existing passenger ship") extend it to all types of passenger ships and offer the possibility of using two different methods for the evacuation analysis: the "simplified method" and the "advanced method". Within the *simplified method*, the total evacuation time is calculated and compared with an allowable time which depends on both the vessel type and the number of Main Vertical Zones (MVZs). The *advanced*

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method uses computational tools to calculate the total evacuation time taking into account many parameters like the behaviour of each passenger when is escaping and the interactions between human factor (gender, age, reduced mobility) and ship layout by means of a virtual reality software.

It is worth to specify the definition of Main Vertical Zones given by SOLAS (Ch. II-2/3.32): they are those sections of the ship having in general a mean length and width not exceeding 40 m, and limited by "A"-class divisions in order to not propagate fire and smoke. Essentially, "A"-class divisions are bulkheads and decks constructed of steel or other equivalent material, which are insulated with approved non-combustible materials in order to limit temperature risings resulting in a fire, as more specifically stated in SOLAS Ch.II-2/3.2.

SOLAS II-2/13.2 (Means of escape) requires that at least two separated means of escape from all spaces on board must be ensured. Each MVZ owns a primary mean of escape, while the secondary ones are placed in the adjacent MVZs. All the means of escape along an escape route like doorways, stairways and corridors are sized in accordance with Chapter 13 of the International Code for Fire Safety Systems (FFS Code). In that Regulation two main cases are considered:

Case 1 (by night) – all passengers in cabins with maximum berthing capacity fully occupied; crew members 2/3 in cabins and 1/3 in service spaces.
Case 2 (by day) – all passengers in public spaces occupied to 3/4 of maximum capacity; crew members 1/3 in public spaces, 1/3 in service spaces and 1/3 in cabins.

The evacuation analysis must be performed at least for the following scenarios:

Scenario 1 – persons as per Case 1; entire ship; evacuation along the main means of escape.
Scenario 2 – persons as per Case 2; entire ship; evacuation along the main means of escape.
Scenario 3 – persons as per Case 1; MVZ with longest evacuation time; evacuation along:
Alternative 1 – secondary means of escape.
Alternative 2 – main means of escape (plus 50% of persons from adjacent MVZs)
Scenario 4 – persons as per Case 2, evacuation as per Scenario 3.

The final objective of the evacuation analysis is the evaluation of the *total evacuation time* and its comparison with an *allowable time n* equal to 80 minutes (reduced to 60 minutes for ro-ro passenger ships and passenger ships with no more than 3 MVZs).

In the "simplified method", the check to be done is the following:

$$\textit{total evacuation time} = 1.25\,(A+T) + 2/3\,(E+L) \leq n \tag{1}$$

where A is the *awareness time* equal to 10 minutes for the night scenarios and 5 minutes for the day scenarios; T is the *travel time* given by the sum of tabular values related to flow time, deck travel time, stairway travel time and assembly travel time properly defined in IMO MSC.1/Circ.1238; E is the *embarkation time* and L is the *launching time*, which sum is fixed to 30 minutes.

In the "advanced method", the travel time, including also the awarness time, is calculated by virtual reality software that considers the probabilistic nature of the process. Then:

$$\textit{total evacuation time} = 1.25\,T + 1/3\,(E+L) \leq n \tag{2}$$

Embarkation, launching and allowable times are the same as in the simplified method. For each scenario, 50 simulations must be run, considering 10 randomly-generated populations. Another important result from the simulations is the identification of possible congestion points (bottlenecks) along the escape routes. By "congestion" is defined an area where population density exceeds 4 persons/m^2 for a significant time. If there are more than 10% of simulations with significant congestions, some means of escape must be modified.

3. Tools

The virtual reality simulators use different pedestrian algorithms, which in turn are based on peculiar mathematical models (statistical models, queuing models, route-choise models, gas-kinetic models, etc.). The main certified software are:

- EVI: developed by University of Strathclyde – Glasgow. The tool allows to evaluate the so-called Evacuability Index, which measures the ability of evacuating a ship within a given time and for given initial conditions. The movement of a large number of passengers and crew members (generically termed *agents*) requires two levels of modeling. At the high level, macroscopic details about the environment topology as well as routing information are given, while at the low level, microscopic details are defined in order to permit the agents to interact with the different obstacles encountered along the route. The combination of macroscopic and microscopic details is termed mesoscopic modeling.

- EXODUS: developed by University of Greenwich. It is based on the interaction of six sub-models, which consider different aspects of the evacuation process (movement, passenger, behaviour, toxicity, hazard and geometry) until ship abandon (i.e., boarding and launching lifeboats).
- ODIGO: developed by the French engineering company Principia. The tool includes a pre-processor, a simulation engine and a post-processor. Through the pre-processor a model describing the general arrangement of decks and related staircases is created from dxf files. The simulation engine instead considers the crowd movement on board ship using a cognitive-reactive behavioural model for agents.
- VELOS: developed by National Technical University of Athens. It is a generic multi-agent software with a wide range of functionalities including virtual reality modeling, as well as crowd microscopic modeling through a library of nearly 20 steering behaviours. The tool can communicate with other packages (e.g., sea-keeping software) in order to take into account the ship-motion effect on passengers' movement, and improving the environment realism.
- AENEAS: developed in cooperation between DNV-GL and TraffGo. Like other similar tools it is a multi-agent software that uses a 3D interface. Its peculiarity is that of discretizing the plans of the ship in a grid of squared cells. Each cell can be free or occupied by a person or an obstacle. Thanks to such a grid the software allows very fast simulations even for large populations.

3.1 AENEAS

AENAES is a multi-agent software where persons (the *agents*) are represented as individuals with independent attitudes, abilities and goals. The software requires a square-cell discretization of the various decks. The cell side is 0.4 m long and each agent can occupy only one cell at each time step.

The following types of cell can be used:

- *Free cells*, which can be occupied by agents during the evacuation. In Figure 1 they are represented by white color.
- *Wall cells*, which represent obstacles (i.e., walls, furniture, etc.) along the escape routes. Consequently, they are blocked and cannot be occupied by agents. In Figure 1 they are black colored.
- *Goal cells*, which represent the objective to be achieved by each agent. The objective may be either an assembly station or a cabin. If there are no goal cells, the simulation cannot be performed. The goal cells are identified by a tag given by the user.
- *Door cells*, which represent doors. They affect the evacuating flow by reducing the agent walking speed. In Figure 2, they are red colored.
- *Step cells*, which represent stairways (both up- and down-stairs) affecting the evacuating flow. In Figure 2, they are cyan colored.

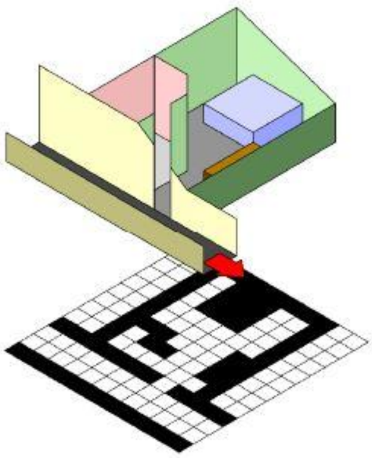


Fig. 1: Detail of a cabin in AENEAS.

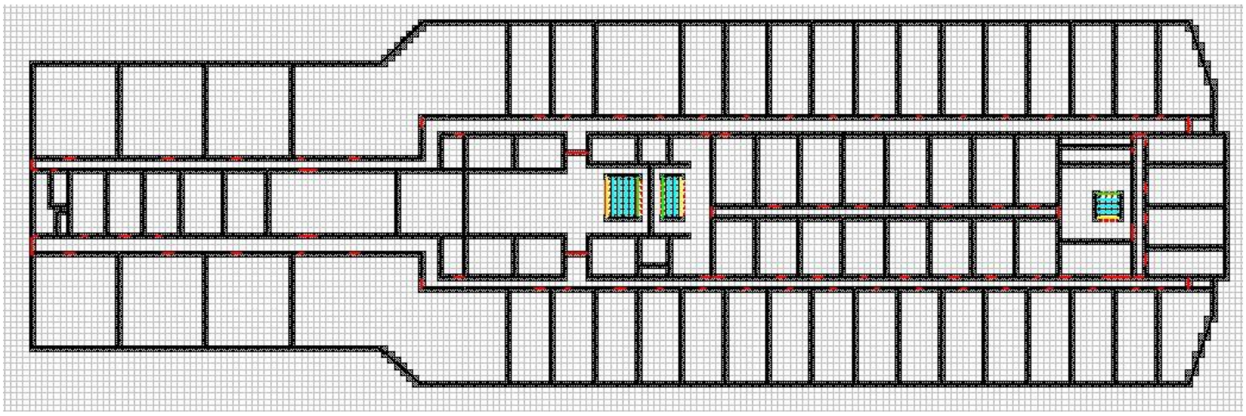


Fig. 2: Square-cell discretization of a deck as processed by AENEASed.

During each time step of the simulation agents move from cell to cell, using the neighbouring free, door or step cells in order to reach its assigned goal cell. The agents follow escape routes, which may be specified either by the user or assigned by default as the way towards the closest goal cell. For orientation, agents make use of the values of a *potential* associated to each cell. For each route the potential of a cell assumes a value that increases proportionally with the distance from the goal cell. The agent finds its way by comparing the potential of the cell where it is standing on with the potentials of the neighbouring cells. There are 8 adjacent cells to take into consideration (see Figure 3).

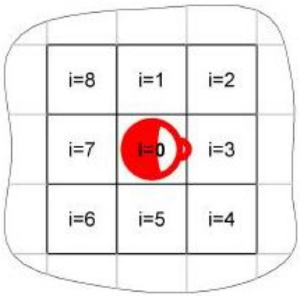


Fig. 3: Cell scheme for agent orientation.

Standing on a certain cell $i = 0$ (central cell), the occupation of an adjacent cell *i* is done on the basis of the greatest probability p_i, calculated as follows:

$$p_i = e^{-\frac{(P_i - P_0)+S}{S}} \tag{3}$$

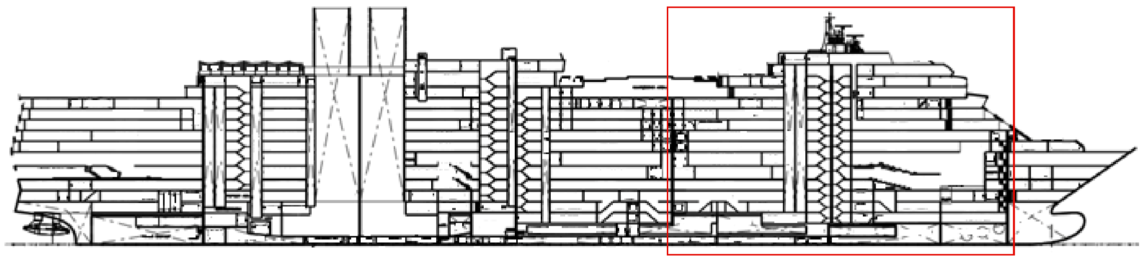
being P_0 the value of the potential of the central cell ($i = 0$) and P_i that of the generic adjacent cell *i*. Moreover, *S* is the value of the *Sway*, a parameter that takes into account the accuracy with which an agent follows the route established through the potentials.

The software is composed by 3 modules:

- *AENEASed*, the editor module by which a CAD drawing in dxf format can be imported and converted into the relevant cellular grid. After such a discretization and a check by the user, it is possible, if the case, to amend the geometry of the decks. Furthermore, it is necessary to distribute the agents inside the vessel and define their escape routes.
- *AENEASsim*, the module that allows to run the simulations and analyze the results. To take into account the random nature of a real evacuation, for each scenario a number (at least 500) of simulations are automatically generated and carried out. The demographic parameters of passengers and crew may be fixed either by default on the basis of the MSC.1/Circ.1238 or properly established by the user according to the actual population present on board. The results of each scenario are synthesized by the probability density function of the evacuation time associated to each simulation (see Figure 6), and through sketches of the decks with the congestion points corresponding to the significant evacuation time (defined as the 95-percentile) to be analyzed (see Figure 7).
- *AENEASview*, the module permits to obtain a 3D representation of the evacuation phases by a video. The video concerns the simulation corresponding to the above-mentioned significant evacuation time.

4. Case Study

An existing cruise passenger ship has been considered to carry out an advanced evacuation analysis. The main dimensions of the ship are indicated in Figure 4 together with its longitudinal view. In particular, the red frame outlines the two MVZs considered for the simulations. In Figure 5 the two MVZs are enhanced.



Length, overall	285.00 m	Gross Tonnage	86300 GT	Speed, max	24.00 kn	Passengers	2667
Breadth, moulded	32.20 m	Deck	11	Speed, cruise	22.00 kn	Crew	933

Fig. 4: The ship considered in the evacuation analysis.

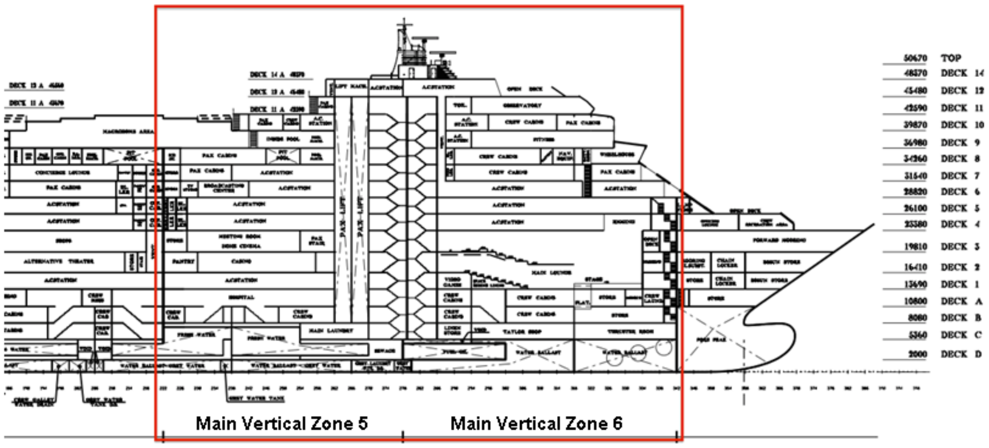


Fig. 5: The MVZs considered in the evacuation analysis.

Tab. 1: Population distribution for each scenario.

	Night scenarios 1-3		Day scenarios 2-4	
Deck	**Passengers**	**Crews**	**Passengers**	**Crews**
C	/	8	/	12
B	/	175	/	88
A	/	89	/	51
1	142	4	202	15
2	0	11	402	22
3	0	17	324	23
4	121	4	0	2
5	150	4	0	2
6	173	4	0	6
7	124	4	0	2
8	108	4	0	2
9	0	14	268	28
10	92	20	0	10
11	20	7	198	12
TOT	***930***	***365***	***1324***	***275***

Tab. 2: Travel times calculated by AENEAS.

Scenario	**1**	**2**	**3**	**4**
t_I [s]	980	667	1483	2344
T [s]	2344			

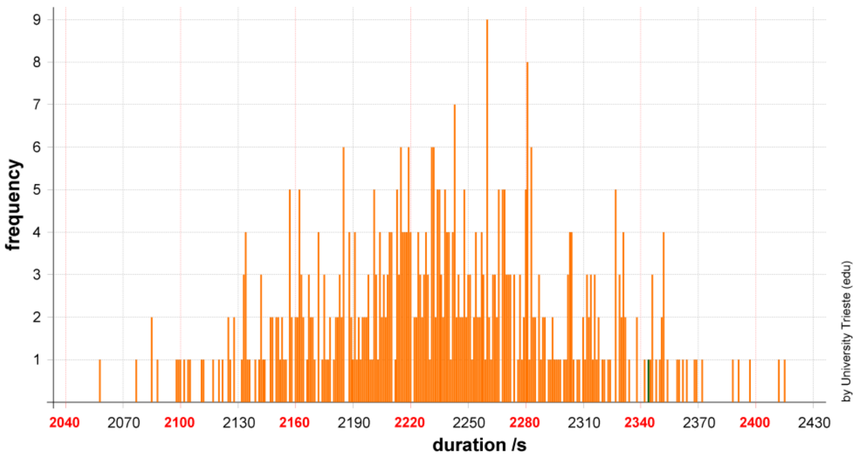


Fig. 6: Probability density function of the scenario evacuation times (green bar is the 95-percentile), as calculated by AENEASsim.

Passenger cabins are located on Decks 4 through 8, passenger public areas are on Decks 2, 3 and 9, while accommodation and recreation areas for the crew are located on Decks D, C, B and A. All the muster stations (assembly stations) are on Deck 3.

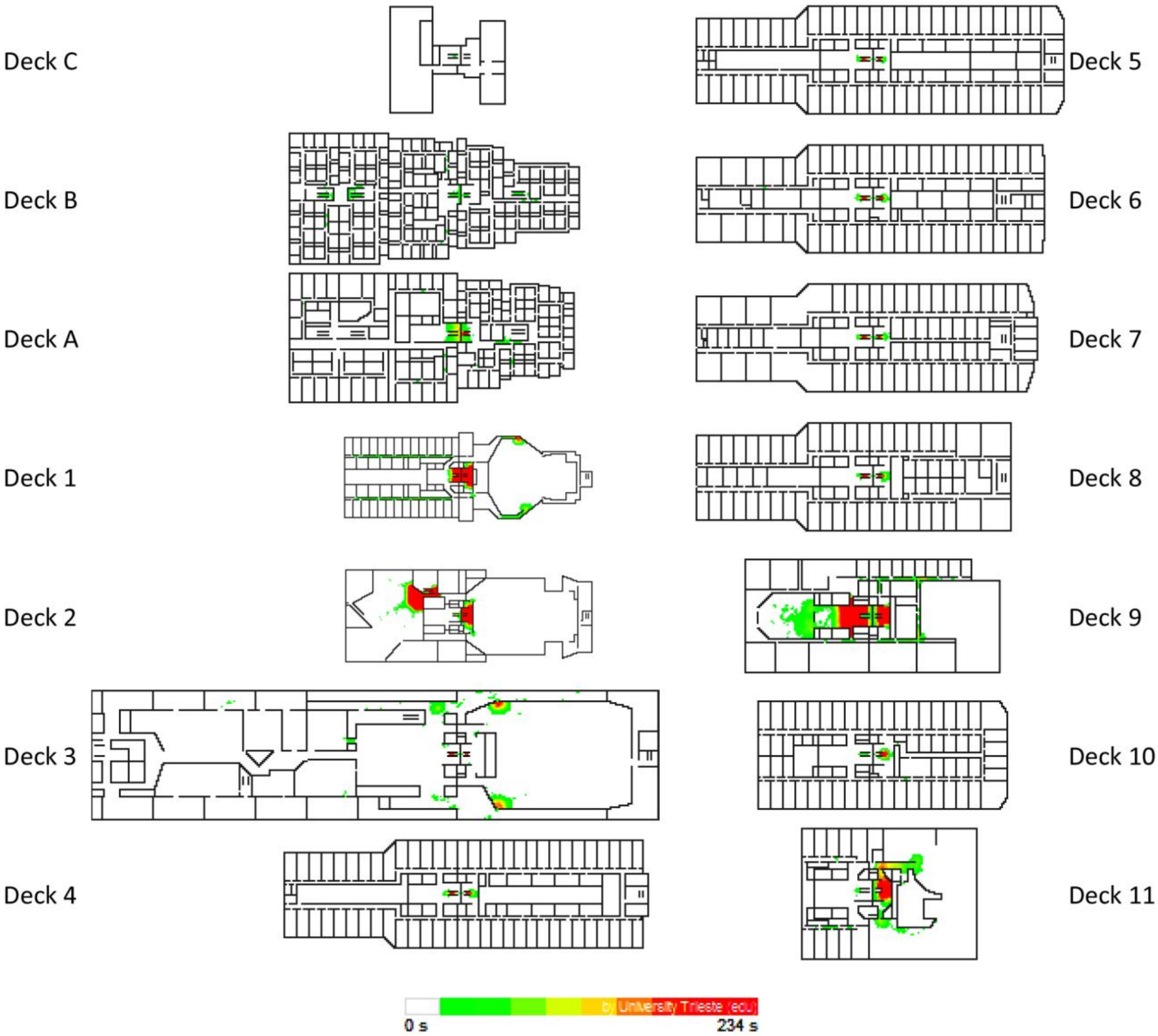


Fig. 7: Representation of the congestion points for a considered scenario as elaborated by AENEASsim.

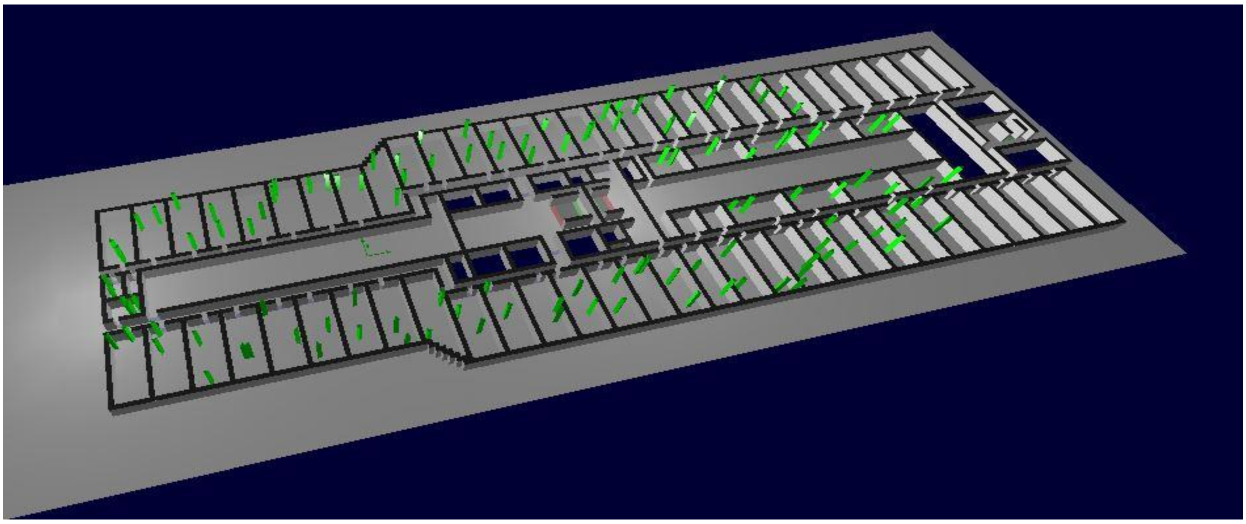


Fig. 8: Screenshot of a simulation time step, obtained by AENEASview.

The evacuation has been simulated for the most populated Main Vertical Zones (MVZ 5 and MVZ 6). The population distributions for night and day scenarios are detailed in Table 1. For each scenario the imposed 500 random-generated simulations have been run and the relevant travel times t_I have been determined (Table 2). Finally, the travel time T is defined as the maximum of the times t_I. In the case study, Scenario 4 presents the highest travel time (2344 s). After a deeper analysis of such a simulation, a congestion point on Deck 2, at the entrance of secondary stairway, can be highlighted.

In accordance with equation (2), the *total evacuation time* has been determined, and the result is equal to 4130 s. So that, the requirement of MSC.1/Circ.1238, which states for a cruise passenger ship an allowable time of 4800 s, is fully satisfied. Despite the performance standard is met, the results obtained could suggest a possible modification of the ship layout in order to further reduce the evacuation time.

5. Conclusions

New IMO Regulations (MSC.1/Circ.1238) for cruise passenger ship impose to perform an evacuation analysis in order to guarantee a safe abandonment of the ship when a significant fire or flooding casualty occurs. The use of specific software to tackle in an advanced manner the dynamics of the escaping crowd is foreseen as well. Currently, only five certified software are available on the market. Up to now the simulation software have been mainly used for ro-ro passenger ship, dealing with at most 1000-1500 persons. In this study, the capabilities of a specific software (AENEAS) to manage a very high number of individuals (about 3600) have been successfully tested.

Acknowledgement

This research has been carried out with the financial support of the “Università degli Studi di Trieste – Finanziamento di Ateneo per progetti di ricerca scientifica – FRA 2014”.

References

Brown R., Galea E.R., Deere S., Filippidis L. (2012) “IMO Inf paper summary – Response time data for large passenger ferries and cruise ship”, Safeguard Passenger Evacuation Seminar, London, United Kingdom.

Chu C., Lu h., Pan C., (2013) “Emergency evacuation route for the passenger ship”, Journal of Marine Science and Technology, Vol. 21, No. 5, pp. 515-521.

Dongkon L., Hongtae K., Jin-Hyoung P., Beom-Jin P. (2003) “The current status and future issues in human evacuation from ships”, Safety Science, Vol. 41, pp. 861-876.

Galea E.R., Brown R.C., Filippidis L., Deere S. (2010) “Collection of evacuation data for large passenger vessels at sea”, PED 2010, Maryland, USA.

Ginnis A.I., Kostas K.V., Politis C.G., Kaklis P.D. (2010) "VELOS: A VR platform for ship-evacuation analysis", Computer-Aided Design, Vol. 42 pp. 1045-1058.

Lopez Piñeiro A., Pérez Arribas F., Donoso R., Torres R., (2005) "Simulation of passengers movement on ship emergencies. Tools for IMO regulations fulfilment", Journal of Maritime Research, Vol. II, No. 1, pp. 105-125

Vassalos D., Christiansen G., Kim H.S., Bole M., Majumder J. (2002) "Evacuability of passenger ship at sea", SASMEX.

Vassalos D., Guarin L., Vassalos G.C., Bole M., Kim H.S., Majumder J. (2003) "Advanced evacuation analysis – Testing the ground on ship", Second International Conference in pedestrian and evacuation dynamics, London, United Kingdom.

Wang W.L., Liu S.B., Lo S.M., Gao L.J. (2014) "Passenger ship evacuation simulation and validation by experimental data sets", Procedia Engineering, Vol. 71 pp. 427-432.

Bucci V., Marinò A., Trincas G., Zanutto G. (2015) "Innovative tools for advanced evacuation analysis of passenger ships", 18th International Conference on Ships and Shipping Research, Lecco, Italy.