

Analysis of Naval Ship Evacuation Using Stochastic Simulation Models and Experimental Data Sets

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Abstract: The study of emergency evacuation in public spaces, buildings and large ships may present parallel characteristic in terms of complexity of the layout but there are also significant differences that can hindering passengers to reach muster stations or the lifeboats. There are many hazards on a ship that can cause an emergency evacuation, the most severe result in loss of lives. Providing safe and effective evacuation of passengers from ships in an emergency situation becomes critical. Recently, computer simulation has become an indispensable technology in various fields, among them, the evacuation models that recently evolved incorporating human behavioral factors. In this work, an analysis of evacuation in a Landing Helicopter Dock (LHD) ship was conducted. Escape routes specified by the ship's procedures were introduced in the model and the six emergency scenarios of the Naval Ship Code were simulated. The crew and embarked troops were introduced with their different evacuation behavior, in addition, walking speeds were extracted from data set collected in experiments conducted at other warships. From the results of the simulations, the longest time was chosen and confidence intervals constructed to determine the total evacuation time. Finally, results show that evacuation time meets regulatory requirements and the usefulness and low cost of the evacuation simulation for testing and refining possible ships' layouts and emergency scenarios.

Keywords: Evacuation modeling, confidence intervals, naval ship, IMO, NATO NSC.

1 Introduction

There are many hazards on a ship that can cause an emergency evacuation, the most severe; flooding, fire or explosion cause thousands of injuries annually [EMSA (2018)]. As an example, over the past 50 years, more than 1,300 maritime accidents caused more than 90,000 victims [Guha-Sapir, Hoyois, Wallemacq et al. (2016)].

A ship is a elaborated vehicle which, in the case of passenger ships, gets more complex, since recent cruise liners reach up a capacity of several thousand people on board [Ginnis, Kostas, Politis et al. (2010)]. The safety of large passenger ships is thus becoming an

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increasingly important issue because of the high number of naval accidents happened worldwide throughout history.

While the number of marine accidents, victims involved and its negative impact on the environment, scarce literature exists on naval disasters and factors affecting the success of safety and evacuation procedures.

1.1 Evacuation modeling background

The evolution of evacuation process modeling has been discussed in several reviews, among them [Kobes, Helsloot, De Vries et al. (2009); Kuligowski (2016)]. The first researches on building evacuation mainly focused on the movement of people in corridors, on stairs and through doors, in addition several researchers collected detailed information about occupant density and travel speed [Fruin (1971)]. More sophisticated methods were developed in the 80's to simulate the complex human behavior through the earliest computer models. In the 90's the models evolved incorporating human behavioral factors. The pure equation-based models were replaced by agent-based models with behavioral rules, agent-to-agent and agent-to-environment interactions [Ronchi and Nilsson (2016)].

Recently, computer simulation has become an indispensable technology in various fields such as engineering, medical science, defense training, logistics, car traffic analysis [Fujii, Yoshimura and Seki (2010); Abe, Fujii and Yoshimura (2017)] or analyzing evacuation from a building [Kuramoto, Furuichi and Kakuda (2015)].

In simple terms, the evacuation process in a crowded space like a sports arena, a building or a ship can be modeled using two basic methods: macroscopic and microscopic. The macroscopic models are based on equations that search for optimal routes for pedestrians, who are typically treated as a whole in which individual behavior can be ignored and their movement may be viewed as network-flow. One of the best known is the model implemented in the SFPE Handbook of Fire Protection Engineering [Nelson and Mowrer (2002)]. As a flow model, walking speeds are determined by evacuee density within each room or corridor and flow through doors is controlled by door width.

The microscopic models [Helbing and Molnár (1995); Ronchi, Kuligowski, Nilsson et al. (2016)], more sophisticated and common at present, take individual movement and uncertain behavior into account, trying to represent realistically the decisions made during the evacuation process by representing each evacuee by an autonomous agent with individual properties, reaction time, travel speed, priority, etc. Moreover, the agents have behavioral rules that modify speed according to the distance between persons, walls, floor tilt or smoke). This work is based on the microscopic approach as most of the models at present.

In order to model human behavior and its uncertainty during evacuation, the two most common approaches are deterministic and stochastic [Klüpfel (2008)]. The deterministic approach is straightforward but it may not be able to represent the variance in human behavior [Gwynne, Galea, Owen et al. (1999); Cuesta, Abreu and Alvear (2016)]. The stochastic approach allows modelling different behaviors starting from the same initial conditions. Three methods can be used to achieve stochasticity: A deterministic model with random inputs, pure stochastic models and finally a combination of stochastic model

and random input [Averill, Reneke and Peacock (2008); Ronchi, Reneke and Peacock (2014)]. With regard to achieve the required stochasticity and consider a full range of occupant behaviors, the definition of the appropriate number of runs for the simulation of a single evacuation scenario is a key issue in egress modelling. This topic is central to this paper and is discussed below.

Related works

The study of emergency evacuation from buildings and large ships may present parallel characteristic in terms of complexity of the layout: compartments, corridors, stairs, escape routes, crowd agent behavior and dynamics, paths and wayfinding [Jørgensen and May (2002); Dimakis, Filippoupolitis and Gelenbe (2010); Balakhontceva, Karbovskii, Rybokonenko et al. (2015); Casareale, Bernardini, Bartolucci et al. (2017)]. Nevertheless, significant differences exist, evacuation in buildings consists of a displacement on a static floor towards exits [Kobes, Helsloot, De Vries et al. (2009)], while ship abandonment requires adapting to ship movements (pitch, roll, trim) and other difficulties that can hinder passengers to reach muster stations or the lifeboats [Balakhontceva, Karbovskii, Sutulo et al. (2016); Sun, Guo, Li et al. (2017)]. Moreover, ship's evacuees need assistance in the embarkation phase even after the ship is abandoned [Nevalainen, Ahola and Kujala (2015)].

Many ship evacuation simulation models employ a stochastic approach for the representation of passengers behavior patterns [Galea, Deere, Sharp et al. (2007); Gwynne, Galea, Lyster et al. (2003); Hurley, Gottuk, Hall Jr et al. (2016); Lee, Kim, Park et al. (2003); Meyer-König, Valanto and Povel (2007); Vassalos, Kim, Christiansen et al. (2002)]. This stochastic approach make sense since if an evacuation drill is repeated using the same conditions and population of the same characteristics, the evacuation will be performed differently obtaining a probabilistic distribution of total evacuation time (T_{ET}). However, two key questions that arise when using a stochastic evacuation model concerns how many simulations are required to obtain a given level of confidence that the predicted results provide a true indication of the expected outcome for the scenario and what should be considered the representative value of predicted parameters such as T_{ET} for a given scenario. Given a distribution of predicted T_{ET} there are several possible values for the more representative T_{ET} such as 95th percentile, longest, mean or median T_{ET} and the choice depends on the purpose of the analysis. If it is part of a risk study, it may be appropriate to take the worst case, i.e., the 95th percentile T_{ET} , if the analysis is more concerned with typical performance, then the mean T_{ET} may be convenient. While there has been some interest in these issues [Lovreglio, Ronchi and Borri (2014); Meacham, Lord, Moore et al. (2004)] only a limited number of studies analyzed ship evacuation procedures and tried to define models to represent such process [Balakhontceva, Karbovskii, Rybokonenko et al. (2015); Galea, Deere, Brown et al. (2014); Meyer-König, Valanto and Povel (2007); Pérez-Villalonga, Salmerón and Wood (2008)]. Thus, more research is needed on improving evacuation procedures based on people's behaviors.

In the case of a naval ship, the abandonment only happens if a serious accident has taken place and the ship is close to sinking due to a missile or terrorist attack, heavy fire,

collision with other ship or rocks, etc. The crew and embarked troops first meet at muster stations and then travel to their embarkment point quickly thanks to systematic evacuation drills. While evacuating, however, the crew should attempt to maintain the ship's watertight and airtight integrity by leaving open as few doors, hatches and other closures as possible [Pérez-Villalonga, Salmerón and Wood (2008)].

1.2 Regulations related with evacuation

1.2.1 Passenger ships

The Maritime Safety Committee (MSC) of the International Maritime Organization (IMO) under the impact of a series of events involving large number of fatalities on passenger ships, approved in 1999 the MSC/Circ. 909 "Interim Guidelines for a simplified evacuation analysis of Ro-Ro passenger ships". The MSC expanded the scope, suggesting the analysis to existing and new passenger ships other than Ro-Ro and adopted in 2002 the Circular 1033 "Interim Guidelines for evacuation analysis for new and existing passenger ships" which offer the possibility of using two distinct methods of analysis: a simplified evacuation analysis and/or an advanced evacuation analysis. The simplified method is deterministic, with passenger movement being modeled through a simple hydraulic scheme. On the contrary, the advanced method is of statistical nature, adopting a microscopic approach to model passenger movement. Although this method is more realistic, both methods are subject to restrictive assumptions and omissions, e.g., ship-motion, fire/smoke influences are not taken into consideration [Ginnis, Kostas, Politis et al. (2010)]. The MSC invited Member States to collect and submit any information and data resulting from research and development activities, full-scale tests and findings on human behavior which may be relevant for the necessary future upgrading of the interim guidelines. As result of information and research [Galea, Deere, Sharp et al. (2007)] the MSC approved in 2007, the IMO MSC/Circ. 1238 "Guidelines for Evacuation Analysis for New and Existing Passenger Ships" [IMO MSC.1 (2007)]. Among other modifications, the response time distribution curve was changed from random uniform curve to a log normal distribution which reflects better the passengers' behavior. The suggested curve was obtained from full scale tests carried out on board a passenger ship. Another change was the safety margin of 600 s for primary evacuation cases and 300 s for secondary evacuation cases (one of the main stairways unavailable) were replaced by adding a 1.25 safety factor to the travel time. Fig. 1 shows the overall evacuation calculation.

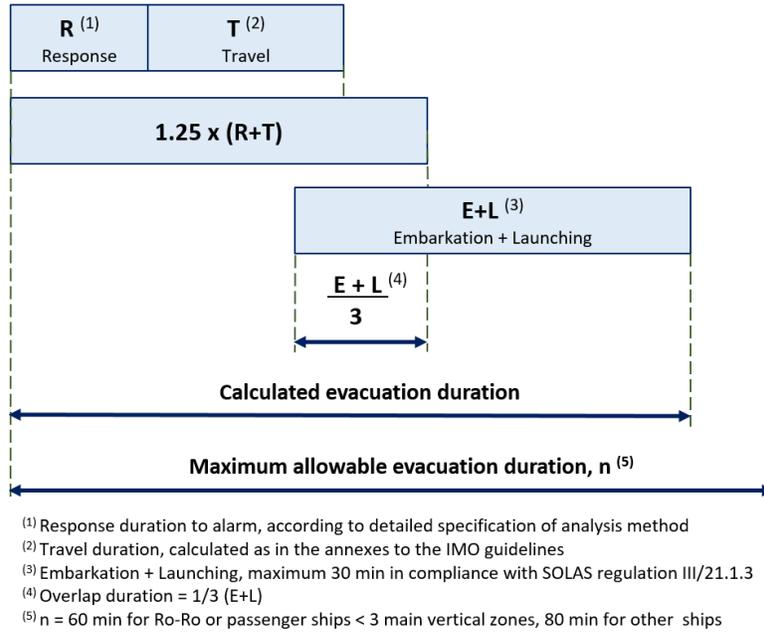


Figure 1: Schematic of the overall evacuation calculation for the advanced analysis

The fire safety engineering uses concepts that tie in closely with the schema of Fig. 1: detection time (D) and alarm time (A), first one is the lap between the fire ignition and the detection by device or first people notice the presence of smoke. Alarm time is the time from detection to a general alarm is released. Thus, the time employed by people to reach a safe place, also called Required Safe Egress Time (RSET) is calculated as a sum of the main four times [Ronchi and Nilsson (2016)]:

$$RSET = D + A + R + T \tag{1}$$

This time required to reach a safe place is compared with the time in which the conditions of the environment are tenable, also called Available Safe Egress Time (ASET) and it can be estimated modeling the hazard scenarios using analytical methods, experiments or Computational Fluid Dynamics. The allowance of design uncertainties may be expressed as a safety factor that can be calculated as shows the Eq. (2):

$$Margin\ of\ Safety = ASET - RSET \tag{2}$$

Finally, the MSC, approved in 2016 the IMO MSC/Circ. 1533 Revised Guidelines on evacuation analyses for new and existing passenger ships, making evacuation analysis mandatory not only for Ro-Ro passenger ships but also for other passenger ships constructed on or after 1 January 2020. While the simplified and advanced methods are admitted, the last one would be preferred, this shall not prevent the use of the simplified method in early design iterations of the ship [IMO MSC.1 (2016)]. As previous Guidelines, it considers four scenarios: case 1 night, case 2 day, cases 3 and 4 like the two previous ones but with a stairway unavailable. In addition, the new Guideline adds

two more cases: case 5 open deck and case 6 embarkation. Next section explains with more detail the cases.

1.2.2 Naval ships

A common requirement in a naval ship design is the analysis of the human factors performance in terms of the crew ability to complete normal operational scenarios. The ability of a naval ship to complete a scenario as quickly as possible may be a matter of survival. If a ship is attacked, it must be able to defend itself in the most efficient way, the crew must move quickly. The analysis of several scenarios can lead to modify the design so that the crew moves more efficiently. This may include alterations such as moving or removing doors, compartments or adding stairs [Andrews, Casarosa, Pawling et al. (2008)]. North Atlantic Treaty Organization (NATO) established in 2004 the Naval Ship Classification Association (NSCA), specialist team comprising Navies and International Association of Classification Societies (IACS). One of the first tasks was to investigate some recent accidents on navy ships, comparing them to similar experiences on commercial ships and it was found as main cause the lack of common rules for addressing safety issues. Thus, NSCA developed a naval equivalent to SOLAS, and after four years of work, the result was the Naval Ship Code, ANEP-77. The latest version is the version f of 2014 [NATO (2014)]. The naval ship code covers the areas of structure, buoyancy, stability and controllability, engineering systems, fire safety, escape evacuation and rescue, radio communications, safety of navigation and carriage of dangerous goods through ten separate chapters. The Chapter 7 Escape, Evacuation and Rescue follows the philosophy of SOLAS and the IMO MSC/Circ. 1238, furthermore introduces additional factors to be considered which are not usually present on civilian passenger ships. The Naval Ship Code (NSC) identifies the need to undertake analysis of escape and evacuation early in the design process, to investigate possible improvements of the ship's escape and Evacuation measures. The code defines six scenarios that cover a range of ship states and watertight integrity:

Case 1, normal night cruising. During this scenario, there is no imminent threat of attack without prior notice, thus most watertight (WT) doors can assume to be opened. Most of the crew and embarked troops are in their cabins and asleep. There would be one team on watch, and they would be at their watch stations.

Case 2a, normal day cruising. This scenario is like the previous case, with most WT doors assumed to be open. The main difference between the two scenarios is that there would be two teams on watch. In both cases, the location of the crew and the procedures depend on the nature of the ship's operations. If an incident occurs, the crew and embarked troops would move to their emergency stations. If the call is given to abandon the ship, then they would move to the muster stations and then disembark the ship by any means possible, be that via lifeboats, life rafts, or by jumping over the side into the sea.

Case 2b, General Quarters (GQ). This scenario differs significantly to the previous cases because the ship is in state action; it is very likely that an attack occurs without warning, thus all WT doors would be closed, and the ship would be ready to deal with any emergency. Crew would be on watch; they and embarked troops will move to the muster stations if call to abandon ship is given. In route to the muster stations, they will find

closed WT doors which will slow their walk towards the muster stations.

The Naval Ship Code as well as the IMO MSC/Circ. 1238 requires a variation of the previous scenarios. In these secondary cases (**3**, **4a** and **4b**) only the main vertical zone, which generates the longest travel time, is investigated. The code provides two possible alternatives for the secondary evacuation scenarios. The alternative 1 considers one complete run of the stairways having largest capacity previously used within the main vertical zone is unavailable for evacuation. The alternative 2 considers that main vertical fire zone will receive 50% of the persons from the largest neighboring vertical fire zone before proceeding to the relevant muster stations [NATO (2014)].

The following initial distributions of crew and embarked troops should be considered. During the normal night cruising (cases 1 and 3) 1/3 of the crew are on watch and should be located as follows: 50% of them should be in service spaces, 25% should be at their emergency stations and 25% should be at the assembly stations. The remaining occupants must be at their cabins. During the normal day cruising (cases 2a and 4a), the crew on watch (1/3) are located as in previous normal night cruising. The rest of the crew and the embarked troops are distributed as follows: 50% in the accommodation spaces (cabin and day spaces) and 50% will be distributed in public spaces.

When ship sails in GQ situation (cases 2b and 4), the crew and embarked troops are in their GQ combat station

Although replications of simulations are still required to be performed for each scenario, only the worst time among all replications is considered. In addition, from the previous times, the longer evacuation time among the six scenarios must be verified by an escape and evacuation demonstration.

1.3 The evacuation process in a naval ship

The evacuation process of passenger and naval ships has many features in common, however, the ships volumes, layouts, passenger characteristics and behavior are very different. Furthermore, the crew and operational aspects of evacuation from naval ship may be very different [Gwynne, Galea, Owen et al. (1999)]. The behavior of pedestrians in both passenger and naval ships: evacuation choices, timing and loss probability, are affected by multiple factors during the whole evacuation process.

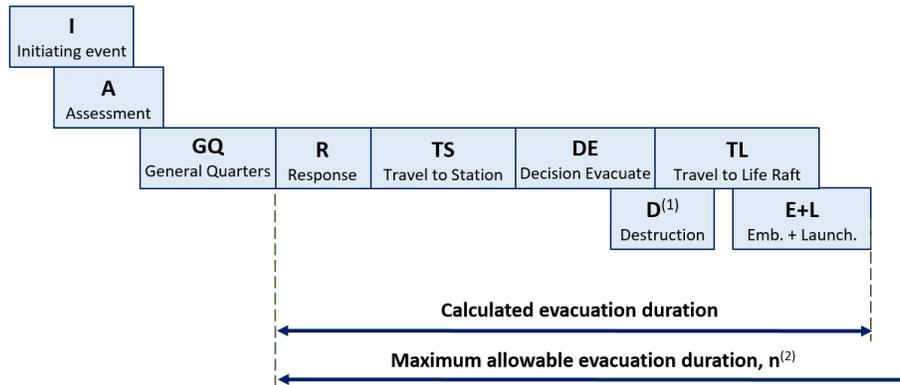
The evacuation process depends on the type of ship, generally can be divided in 4 phases [Klumpf (2008); Kobes, Helsloot, De Vries et al. (2009); Nevalainen, Ahola and Kujala (2015)]: response time when an alarm is activated, travel time, reach the safe place, embarkation and launching duration.

During response phase people try to collect information about the situation and observe how other people behave. In the case of passenger ships, this pre-movement time could be significantly long, because people may ignore alarm signs and try to keep carrying-on their personal belongings [D'Orazio, Spalazzi, Quagliarini et al. (2014)]. In a naval ship, both crew and embarked troops have conducted evacuation drills, know the ship and conduct a disciplined behavior, thus the response time will be shorter.

The travel time depends on, corridors and stairs congestion, wayfinding of muster stations, dynamic conditions of the ship (heel), sea state, smoke, crowd dynamics

[Balakhontceva, Karbovskii, Rybokonenko et al. (2015); Cho, Ha and Park (2016); Lovreglio, Ronchi and Borri (2014); Sun, Guo, Li et al. (2017)]. Crew and passengers must choose the best path to move from their initial position to a muster station, and then the lifeboat deck.

In a naval ship the ship's status determines where the personnel are located and the conditions of the ship. The most common are normal cruising and General Quarters (GQ). When ship sails in normal cruising, the crew usually work in 3 (more usual) or 4 watches. As stated above, 1/3 of the crew are on watch and the rest is distributed depending on it is day or night. When ship sails in GQ situation, the crew have to stop what they are doing and immediately go to their GQ combat station. This situation requires the crew members to occupy their position as soon as possible and the Commander must be informed about any fault. In both status, normal cruising and GQ, if the decision of abandon the ship is taken (DE) and there is a risk that the enemy can access the wreck, a team is appointed to destroy (D) combat consoles and confidential information. The Fig. 2 shows the evacuation process.



⁽¹⁾ Destruction of all of classified publications and equipment

⁽²⁾ $n = 60$ min for Ro-Ro or passenger ships < 3 main vertical zones, 80 min for other ships

Figure 2: Schematic of the overall evacuation process for a naval ship

1.4 Evacuation time confidence interval

The IMO guidelines MSC/Cir. 1238 [IMO (2016)] have recently been updated, specifying that 500 simulations runs must be performed and their 95th percentile represents the predicted evacuation time value, as opposed to the older versions of the IMO which indicated that 50 simulations were sufficient.

A methodology for drawing design conclusions without the need of 500 simulations and a convergence criteria for stochastic evacuation models based on five measures is provided by some authors [Grandison, Deere, Lawrence et al. (2017); Ronchi, Reneke and Peacock (2014)]. The first two measures are based on comparing the difference between the mean and standard deviation of T_{ET} for j simulations against the mean and standard deviation obtained for $j-1$ simulations with a specified tolerance. The other three measures are based on functional analysis [Averill, Reneke and Peacock (2008)] which compare properties of the average overall egress curve (i.e., the number of exited agents

vs. time) for j simulations against properties of the average overall egress curve for $j-1$ simulations. This measure was incorrectly specified and later corrected in Galea et al. [Galea, Deere, Brown et al. (2014)], the representative T_{ET} is the mean value of all the T_{ETS} generated together with the standard deviation of the T_{ETS} and i and therefore not suitable for assessing convergence of τ .

This paper assumes Grandison's approach based on the construction of a point estimator of evacuation time and different authors have studied an inferential approach to this parameter based on confidence intervals [Grandison, Deere, Lawrence et al. (2017)]. Thus, Grandison et al. show in their work that there is no need to run such a large number of simulations and to estimate the value of the 95th percentile of the population evacuation time using the confidence interval (CI), which indicates that this value is within the interval with a fixed confidence. Given an ordered sample, for each number of iterations carried out, the lower and upper CI values are indicated in Tab. 1, as well as the value estimated by means of the IMO, which naturally is always within the CI.

Table 1: Confidence interval values

Number of repetitions	Point Estimate	Lower IC (95%)	Upper IC (95%)
50	T_48	T_43	N/A
100	T_96	T_89	T_100
150	T_143	T_136	T_148

It should be pointed out that for 50 simulation runs it is impossible to define the upper limit of the CI for the required confidence [Grandison, Deere, Lawrence et al. (2017)]. But in any case, lower limit of the CI could always be defined and the maximum value (T_{50}) is included to limit the upper value. Therefore, in the results section, the two estimates for the 95th percentile of the evacuation time will be given, in addition to the rest of the statistical analyses that are carried out.

2 Methodology

This study consists of the following main phases:

- Experimental data sets of speeds in naval ships.
- Modeling LHD ship from general arrangement drawings.
- Modeling crew and embarked troops: situation depending on the case studied, behaviors, speeds.
- Simulation modeling tool.
- Performing simulations, study variability, proposed confidence interval and analysis of results.

2.1 Experimental data sets of occupants in naval ships

Real data of crew drills in corridors and stairs were collected onboard of two frigates and one LHD ship of the Spanish Navy and used in previous works [Pérez-Villalonga, Salmerón and Wood (2008); González-Cela, Bellas, Carreño et al. (2019)]. As stated below, the crew and embarked troops know well the ship, perform evacuation drills, and are in very good physical condition. Tab. 2 shows the age and sex distribution. The

average population age of the crew in a Spanish Navy ship is 25.8 for women and 31.1, females are younger than males, which results in some higher velocities at stairs and ladders. Tabs. 3 and 4 show the walking speeds through corridor, stairs and ladders (vertical steps) measured at these drills and have been slightly altered for confidentiality reasons. As aforementioned, in a naval ship, both crew and embarked troops have conducted evacuation drills, are familiar with the ship and conduct a disciplined behavior, thus reaction times and walking speeds are better than those suggested in IMO Circulars.

Table 2: Age and sex of crews in Spanish Navy ships

Sex	Age	% of Total
Females	< 30	12%
	30 - 50	3%
Males	< 30	42%
	30 - 50	43%

Table 3: Walking speed through corridors

	Sex	Corridors (m/s)
IMO Crew (uniform distribution)	Females	(0.93; 1.55)
	Males	(1.11; 1.85)
Navy Crew (normal distribution)	Females	(1.48; 0.31)
	Males	(2.49; 0.99)
Embarked Troops (normal distribution)	Females	(1.16; 0.27)
	Males	(1.61; 0.21)

Table 4: Walking speed on stairs

	Sex	Stairs down (m/s)	Stairs up (m/s)	Ladders up (m/s)
IMO Crew (uniform distribution)	Females	(0.56; 0.94)	(0.47; 0.79)	N/A
	Males	(0.76; 1.26)	(0.50; 0.84)	N/A
Navy Crew & Embarked Troops (normal distribution)	Females	(1.07; 0.15)	(0.93; 0.09)	(0.29; 0.07)
	Males	(1.10; 0.25)	(1.01; 0.11)	(0.39; 0.09)

2.2 Modeling LHD amphibious ship

The naval ship chosen for this study is a landing helicopter dock (LHD) designed for broad types of mission profiles: amphibious ship for landings and land support operations, transport of Army forces, aircraft-carrier, and non-combatant operations: humanitarian aid, evacuation from crisis zones amongst other. The ship dimensions are: overall length of 231 m, beam of

32 m, draught of 6.9 m and displacement of 26,000 tons. Multi-functional garage and hangar space on two levels covers 6,000 m² with capacity for 6,000 tons load on each level.



Figure 3: Landing Helicopter Dock ship (www.armada.mde.es)

The first step to modeling the ship is to draw the layout of the decks with the rooms, corridors, common areas and the stairs between decks. Fig. 4 shows the 6 decks and 6 levels of the model.

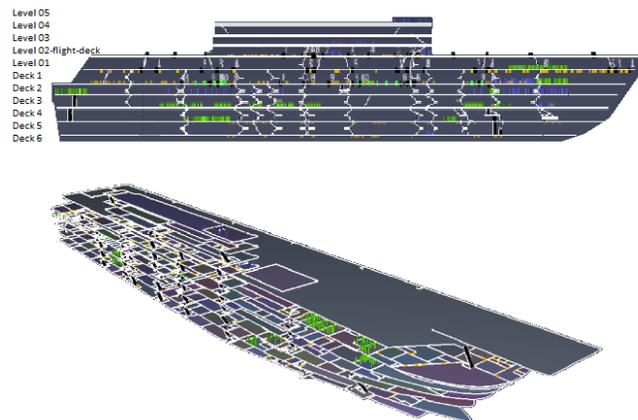


Figure 4: LHD model with decks and occupants

2.3 Modeling crew and embarked troops: behaviors and speeds

In order to evaluate the six scenarios considered in the NSC, a series of simulations were performed. Simulations allow measuring the evacuation time of the crew and embarked forces. The following variables were considered for simulating the CA evacuation:

- Crew speed: normal distribution as seen in Tabs. 3 and 4. The speed values are based on real data collected at different Spanish Navy ships, although they have been slightly altered for confidentiality reasons, which has a minor influence on the results. In passenger civil ships, the walking speed is given in tables for passenger population groups, and is sampled from a uniform distribution with data from scientific research on pedestrian dynamics [Ando, Ota and Oki (1988); Gwynne, Galea, Owen et al. (1999)]. In this study, the crew of the LHD ship knows very well the ship layout and do regular evacuation training drills, thus, walking speed data collected fit better to normal distribution.
- Initial delay: it was estimated as follows: uniform distribution [3;4] min for 1 and 3

night cases, [1;2] min for 2a and 4a day cases and no delay for 2b and 4b GQ cases because crew is ready for an emergency response or awareness time (R). In passenger ships is longer: 10 min for night-time scenarios and 5 min for daytime scenarios. According to some studies on evacuation [Galea, Deere, Sharp et al. (2007)], the pre-evacuation times fit a truncated logarithmic distribution but other studies consider more suitable the normal distribution [Casadesús Pursals and Garriga Garzón (2009)]. Usually, building evacuation experiments are simulated with a heterogeneous population (ages, mobility) so, pre-evacuation times are longer and an asymmetrical distribution fit better. In a naval ship the crew constitutes a considerably homogeneous population and the pre-movement time must be shorter and more uniform.

- Behaviors: crew and embarked forces follow different behaviors that also depend on the emergency scenario (six NSC cases). 13 different behaviors were identified and assigned to each occupant depending on the six scenarios.

2.4 Simulation modeling tool

As stated below, the evacuation process can be modeled using two basic methods: network flow model and a more complex discrete-event model that considers individual agent movements and uncertain behavior (inverse steering mode). Both approaches are possible with the pedestrian egress software Pathfinder [Thunderhead Engineering (2017)]. The network-flow approach is based on the model presented in the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering [Nelson and Mowrer (2002)]. In addition, the steering mode model, is based on the idea of inverse steering behaviors firstly introduced by Reynolds [Reynolds (1999)] and later refined by Amor et al. [Amor, Obst and Murray (2003)]. Inverse steering behaviors improve the original steering concept by evaluating costs of a discrete set of possible solutions.

Pathfinder's inverse steering mode allows a complex behavior to emerge from the movement algorithms, eliminating the need for explicit door queues and density calculations. Pathfinder uses a 3D geometric model. Within this geometric model is a navigation mesh defined as a continuous 2D irregular triangulated surface referred to as a "navigation mesh." Evacuees move on this navigation mesh and ignore the obstructions that are represented as gaps in the navigation mesh, as shown in Fig. 5. The evacuees walk in the rooms whose boundaries cannot be crossed, the travel between two rooms occurs through doors which are represented as green lines. The exit doors are on the exterior boundary of rooms.

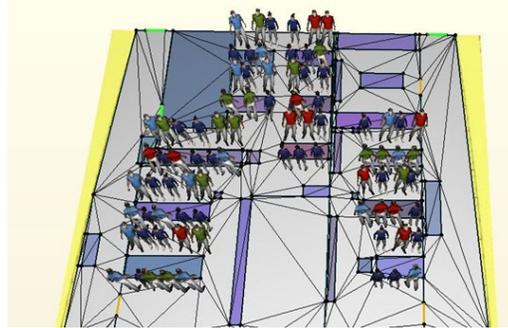


Figure 5: Triangular mesh for evacuation paths in the ship mess hall

The evacuees follow a seek curve and their movement is controlled by a combination of steering mechanisms and collision handling. These mechanisms allow the evacuee to deviate from the path while still heading in the correct direction toward their goal.

Parameters

The triangular mesh can be parametrized by a max. edge length parameter. Likewise, each evacuee can be characterized by a set of attributes: body dimensions, comfort distance, speed, speed modifiers in stairs and elevators, acceleration, wait and delay times, waypoints. A sensitivity analysis to determine the influence critical parameters have on the total evacuation time [Salgueiro, Jönsson and Vigne (2016)] revealed that speed, occupant size, and max edge length of the mesh have a very strong influence on the evacuation time.

Behaviors and goals

Each evacuee has a behavior that dictates a sequence of goals that the evacuee must achieve in the simulation. There are two main types of goals: idle goals and seek goals. Idle goals are ones in which an evacuee must wait at a location until an event occurs, such as a time-interval elapses or an elevator reaches a discharge floor. Seek goals are ones in which an evacuee moves toward a destination, such as a waypoint, room, elevator, or exit [Thunderhead Engineering (2017)]. Depending on an evacuee’s current scripted behavior, they will be in one of two states as shows Fig. 6:

- Seeking: the evacuee is trying to follow a path to some destination.
- Idling: the evacuee is waiting for a specified amount of time.

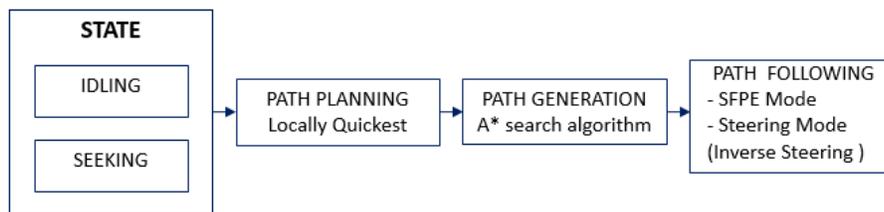


Figure 6: Steering mode procedures and algorithms

Path planning

There may be multiple paths to reach the destination, each of these paths has a length, a number of people along the corridors and rooms, smoke and sail conditions like heeling and tilt. The shortest route may not be the fastest route to the destination for a particular evacuee. The model uses the locally quickest approach to achieve the fastest path for each evacuee. It plans the route sequentially, in each moment evaluates a cost function with local information about the evacuee's current room and the structure of the building (rooms, corridors and stairs). In the current room, the distance to the doors and the queues at those doors are data for the cost function. Outside the room, the distance from those doors to the current destination (seek goal) is also a data for the cost function. The locally quickest method uses these data to choose the door in the current room with the lower calculated cost.

Path generation

When an evacuee has a destination to seek, they need a plan for how to reach the destination, a path to follow, and a way to follow the path while accounting for dynamic obstacles along the path, such as other evacuees. Pathfinder uses the A* star search algorithm to create waypoints that form the path [Hart, Nilsson and Raphael (1968)].

Steering behaviors

The possible steering behaviors are *seeking*, *idle separate*, *seek separate*, *seek wall separate*, *avoid walls*, *avoid evacuees*, *pass*, *lanes*, and *cornering*. Most behaviors award a cost between 0 and 1 for each sample direction. The net cost for a direction is a weighted sum of these values [Thunderhead Engineering (2017)]:

- *Seeking* behavior steers the evacuee to travel along a seek curve. Given the sample direction v , and a seek curve sc , the seek behavior bases its cost (C_{seek}) on the magnitude of the angle between v and the tangent to sc .
- *Idle separate* behavior steers evacuees to maintain a desired distance away from other evacuees and is used when evacuees are in an *idle* state. A desired absolute movement vector (direction and distance) is calculated as the average of evacuee separation vectors. The cost C_{isep} varies from 0 to 1 in function of the movement vector.
- *Avoid walls* behavior detects walls and steers the evacuee to avoid collisions with them. This behavior projects a moving cylinder ahead of the evacuee in the direction of the projected point. The cost (C_{aw}) reported by this behavior is based on the distance the evacuee can travel in the direction of the projected point. It is also affected by the angle at which the evacuee hits the wall.
- *Avoid occupant's* behavior steers an evacuee to avoid collisions with other evacuees. This behavior first creates a list of evacuees within a frustum whose size and shape are controlled by the velocity of the evacuee. Then the behavior projects a moving cylinder ahead of the evacuee in the sample direction. This cylinder is tested against another moving cylinder for each nearby evacuee. If none of the moving cylinders collide the cost (C_{ao}) is zero, otherwise the cost is based on how far the evacuee can travel prior to the collision.

- *Seek separate* behavior spreads out evacuees to maximize their travel speed as calculated by the evacuee’s speed-density curve and Fruin’s spacing-density relationship. The speed is then predicted at that location from the density and the evacuee’s speed-density curve. The predicted speed is then used to calculate the cost C_{ssep} .
- *Seek wall separate* behavior steers evacuees such that they want to main a boundary layer distance away from walls.

Final direction cost

The final cost for a sample direction is a weighted sum of the individual behavioral costs:

$$C_{ds} = 0.5 \cdot C_{seek} + W_{isep} \cdot C_{isep} + W_{ao} \cdot C_{ao} + W_{aw} \cdot C_{aw} + W_{ssep} \cdot C_{ssep} + W_{swsep} \cdot C_{swsep} + W_{lanes} \cdot C_{lanes} + W_{cnr} \cdot C_{nr} + W_{pass} \cdot C_{pass} \tag{1}$$

The weights depend on the evacuee’s current state and are defined in the following table.

Table 5: Weights of steering behaviors (seconds)

Steering behavior	Weight	State=Idle	State=Seeking
Seek	w_{seek}	0.5	0.5
Avoid occupants	w_{ao}	1	1
Avoid walls	w_{aw}	1	1
Idle separate	w_{isep}	1	0
Seek separate	w_{ssep}	0	2
Seek wall separate	w_{swsep}	0	1
Lanes	w_{lanes}	0	1
Cornering	w_{cnr}	0.2	0.2
Pass	w_{pass}	0	0.5

2.5 Performing simulations and results

The simulation was conducted with a total of 1,119 people: 273 crew and 846 embarked troops. Simulations were performed on the assumption that the lightweight garage at Deck 1 is half full, so the muster stations are located in the flight deck, Level 02 according with the evacuation procedure of the ship. The crew and embarked forces wait at muster stations the order of abandon the ship, if it happens, they descend to Deck 1 and disembark by inflatable evacuation slides to the life-rafts. In order to simulate the cases 3, 4a and 4b, the main vertical zone in portside have 50% of the stairways unavailable for evacuation.

2.5.1 Queues

The following figures show the six scenarios and the deck where longest, and slowest queues are formed. Tab. 6 shows the color code for represent the occupants’ density in the queues, that vary from 0 to 3 occupants per square meter. Thus, the areas with the highest density should preferably be analyzed in the early stages of the ship design, as well as in the evacuation procedures in order to try to minimize the queues and the T_{ET} .

Table 6: Density code color for queues

F: more than 2.5 occupants/m ²	F
E: $2.25 \leq \text{occupants/m}^2 < 2.5$	E
D: $2 \leq \text{occupants/m}^2 < 2.25$	D
C: $1.5 \leq \text{occupants/m}^2 < 2$	C
B: $0.5 \leq \text{occupants/m}^2 < 1.5$	B
A: less than 0.5 occupants/m ²	A

Fig. 7 shows the queues in Level 01 located at 23.75 meters above baseline and just under Level 02 (flight-deck) and just above the Deck 1. In the Level 01 the higher occupants' density is attained. Notice that night cases present more traffic than day ones because major part of crew and embarked forces are at their cabins, Obviously, cases 3, 4a and 4b present higher densities because some stairways are disabled. The biggest queues are produced in a ladder at bow for cases 1 night, 3 night and 4b GQ. The design of the ladders could be improved enlarging the bow ladder or redirecting occupants to main stairways more astern.

After review the images showing the queues in all decks, it is evident that some agglomerations occur in the narrow zones of corridors near stairways, in addition, it seems that in a few pathways the stairs capacity is not sufficient for evacuate certain occupant's flows.

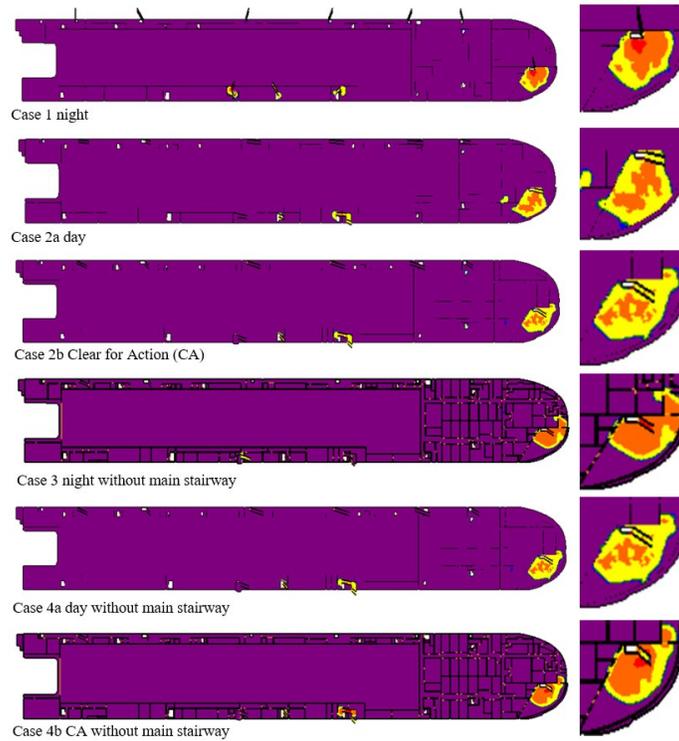


Figure 7: Level 01 density of occupants in queues, six cases

As a preliminary step to abandoning the ship, the crew and embarked forces meet in the five muster stations located at the Deck 02 (flight-deck). Fig. 8 shows the queues in stairs and ladders that present higher densities where occupants may be redirected. in order to reduce the queues.



Figure 8: Level 02 flight-deck density of occupants in queues near muster stations

2.5.2 Pathways

Fig. 9 shows the pathways that the personnel have traveled in their evacuation across the Deck 1 at 21 meters above the baseline, just under the Level 01. This deck presents larger and varied pathways thus it was chosen to be shown instead other decks. Pathways of embarked forces are blue, and pathways of crew are green. It is remarkable the little variability that occurs within the day and night cases.

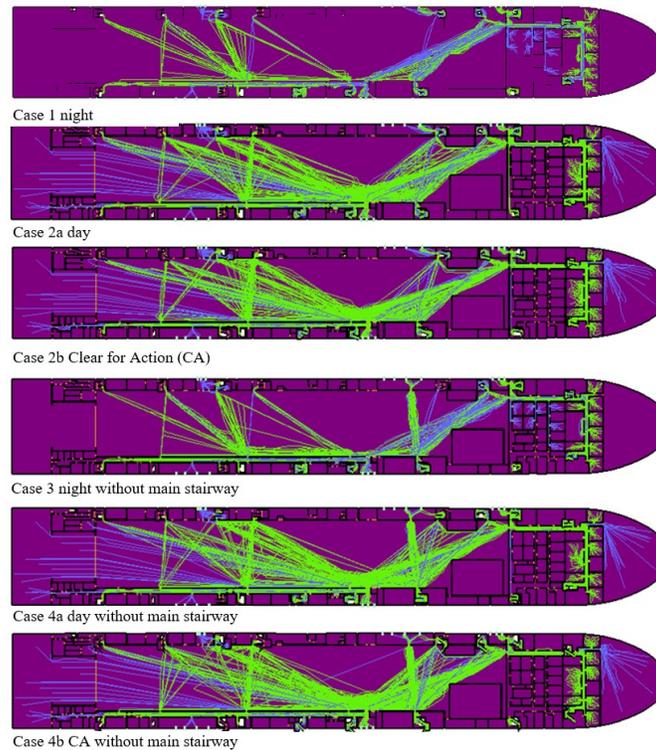


Figure 9: Deck 1 pathways of occupants, six scenarios of NSC

During daytime scenarios, most of crew and embarked forces are outside their cabins, so routes are more varied along the ship, while at night, as the majority of the crew and embarked forces are resting in their cabins, they follow more homogeneous paths, as can be observed in Fig. 9.

As stated above, crew and embarked forces meet in the five muster stations located at the Deck 02. Fig. 10 shows for Case 1 the pathways that the crew (green) and embarked forces (blue) have traveled across the Deck 02 (flight-deck) in their evacuation to the five muster stations.



Figure 10: Pathways of occupants going to their muster-stations in flight-deck, Case 1

2.5.3 Evacuation time results, statistical analysis

After performing the simulations characterized in the previous sections, the results obtained are analyzed. In the statistical data collected by Tab. 7 for the six cases it is observed that there is a notable difference between the first 3 cases, with every main stairway operative and the last 3 with some of the stairways disabled.

The average evacuation times in the first three cases are lower than their respective last three cases. The typical error due to variations produced by distorting causes, both unknown and known is higher in last three cases than in the first three ones. It can also be pointed out that the maximum and minimum values of the first three cases are lower than those of the last 3 cases, with the exception of case 1, which is very similar to case 4a, and higher than case 4b, demonstrating that the night factor is of vital importance. As for the asymmetry coefficient, it can be appreciated that in the first 3 cases, this is positive indicating that there are more values located to the right and therefore there are more data with times above the average. On the other hand, in the last 3 cases, the values of the symmetry coefficients are closer to zero implying that the deviation to the right and left is small and therefore closer to a normal distribution.

Once the descriptive analysis of the data obtained is conducted, a box diagram is used to show the results of the evacuation with its corresponding explanation.

Fig. 11 shows the distribution of the studied results in a single image, it can be noted that in first three cases the evacuation time is shorter than in last three cases, in which, some occupants were forced to use alternative paths due to the lack of some stairways. Even so, T_{ET} of case 1 is slightly greater than case 4b, because the waiting time in the night case is greater than the delay time produced by the queues of case 4b.

The values obtained in case 1 are the higher of the three first cases. This is due to the fact that the first case corresponds to night and therefore the reaction time is longer, case 2a corresponds to day and therefore the reaction time is shorter than in the previous case, and finally the third case corresponds to GQ where the reaction time has been considered negligible. For the three last cases with some main stairways disabled the total evacuation time follows the same schema.

Table 7: Statistical data of six cases (seconds)

	Case 1 Night	Case 2a Day	Case 2b GQ	Case 3 Night	Case 4a Day	Case 4b GQ
	Stairways operational			Main stairway disabled		
Mean	2855.60	2544.48	2285.36	3019.48	2860.36	2746.98
Typical error	15.99	21.91	22.76	29.97	24.10	34.60
Median	2831.53	2521.91	2246.28	3022.16	2839.03	2759.66
Std. deviation	50.55	69.29	71.98	94.78	76.22	109.40
Curtosis	1.51	-1.80	0.09	0.33	-1.345	-0.45
Asymmetry coeff.	1.53	0.39	1.159	-0.38	0.40	-0.62
Rank	150.00	176.75	209.00	329.50	213.75	313.00
Minimum	2817.53	2471.78	2219.28	2837.78	2756.28	2569.53
Maximum	2967.53	2648.53	2428.28	3167.28	2970.03	2882.53

As Fig. 11 shows, there is not any outlier, so all values are within the limits. This shows that for each case, the simulation runs conducted have a great consistency.

It can also be pointed out that case 2b and case 3 are the limits since 2b present the shortest evacuation time and case 3 present the longest evacuation time. Finally, the

medians of the last 3 cases are more centered, it must therefore be concluded that there are a greater number of values close to that median following a normal distribution.

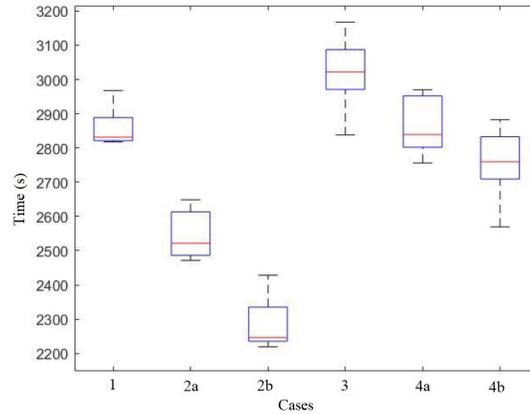


Figure 11: Box-plot of the six cases

The Lilliefors test was used to demonstrate whether the normal distribution hypothesis can be rejected. In first three cases, the test has indicated that the hypothesis is rejected and therefore, the three cases are not close enough to a normal distribution, whereas in cases 3, 4a and 4b, the Lilliefors test indicates that they are close enough to normal distribution. At first glance it may seem illogical since in all cases the speed values are within the same range, but speeds vary depending on the paths, since the stairways have and ladders have different reduction factor, the speed in the latter being lower. Therefore, in the last 3 cases, when suppressing some stairways, the personnel are guided by a more homogeneous terrain and therefore the times are similar.

Figs. 12 and 13 show the distribution tests and histograms of the total evacuation times for the different cases. It can be pointed out that the last 3 cases are more similar to a normal distribution than the first 3 ones. In addition, the results obtained after the Lilliefors test are corroborated with the results analyzed in the previous sections.

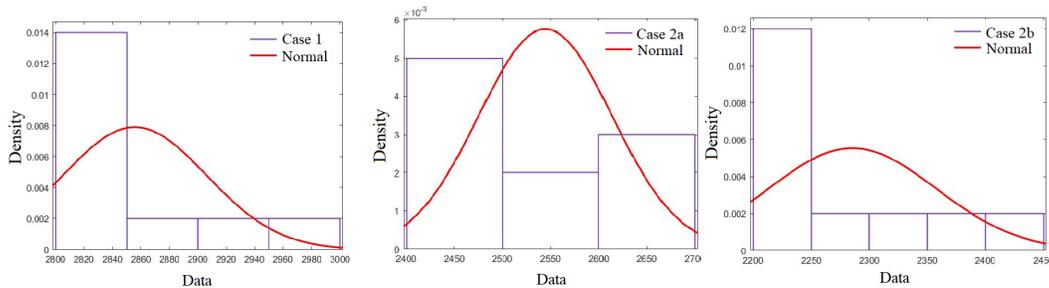


Figure 12: Distribution test of cases 1, 2a and 2b

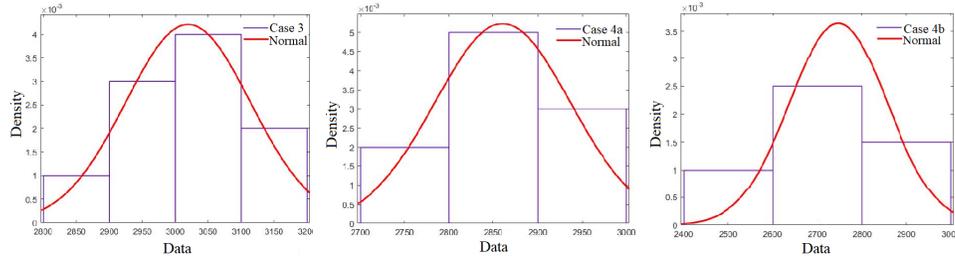


Figure 13: Distribution test of cases 3, 4a and 4b

Following the procedures described above and carrying out the descriptive analyses of the samples obtained, we conclude about the evacuation time for each case studied and thus be able to verify that in any case they are within the regulations in force. Tab. 8 shows the specific values of the confidence interval described in the corresponding section. Remarking that only the in the case of 50 simulations it does not apply to calculate the upper limit, the maximum value (T_{50}) is included to limit the upper value of T_{ET} population.

Table 8: T_{ET} estimations of six cases (seconds)

	Case 1 Night	Case 2a Day	Case 2b GQ	Case 3 Night	Case 4a Day	Case 4b GQ
	Stairways operational			Main stairway disabled		
Lower CI (T43)	2830.1	2488.8	2243.4	3008.4	2831.4	2744.5
Maximum (T_{50})	2967.5	2648.5	2428.3	3167.3	2970.0	2882.5

Therefore, the total evacuation times for all cases are shorter than maximum allowable evacuation duration, $n=3,400$ s established by IMO and NSC for Ro-Ro ships, as shown in Figs. 1 and 2. Moreover, a waiting time of 200 s was included the behavior of both crew and embarked forces at musters stations. Anyway, the real utility of the modeling tool is to easily test alternatives in order to improve the evacuation procedures considering different scenarios.

3 Conclusions

In the present work the study and modeling of a naval ship evacuation has been carried out. For this purpose, evacuation bibliography has been reviewed, as well as the increasingly strict current regulations, which attempt to consider all the situations that can occur when a ship is abandoned and thus be able to secure maximum evacuation times with greater safety.

To carry out the advanced evacuation analysis, the Pathfinder simulation software was used, it allows to represent the ship in a faithful manner following the general layout plans and the evacuation procedures. The importance of the location of corridors, doors, stairways and ladders along the ship has been highlighted as these are the elements that most favor the formation of queues. Certain conditions or hypotheses have been

established for the correct estimation of the evacuation time since, as it is a simulation software, it is necessary to configure precisely and completely the behavior variables that can condition the evacuation of crew and embarked troops.

After a qualitative study of the images showing the queues and trajectories, the importance of reaction times and the situation of the personnel prior to abandonment is demonstrated. Added to this, is the importance of having all escape routes operational, thus preventing staff to choose alternative pathways.

Results were statistically analyzed by means the Lilliefors test, according to which, last 3 cases follow a normal distribution due to the disablement of some stairways and forcing personnel to use ladders that reduced their speed, thus making the total speeds existing in the evacuation more homogeneous.

After the qualitative and statistical analyses, it can be concluded that the zones of corridors near stairways must be wider, as well as the main stairways with greater flow in order to foresee the disabling of a few of them due to an attack or a fire. In addition, the evacuation procedures and training drills must consider alternative routes in case of some main vertical zones (stairway enclosures) are disabled due to an attack or a fire.

Bearing in mind the above conclusions, it should be highlighted the importance of demonstrate the effectiveness of a ship's evacuation system in two stages of the ship's lifecycle: an initial stage during the early steps of the design process, when the layout changes have less impact on the project cost and on the other hand, during the ship's lifespan, it is critically important the preparation of the crew and embarked troops in the execution of the evacuation, abandonment and rescue duties.

Finally, a future line of work could be to conduct further simulations adding sea conditions, heeling and trim effects on walking speed, moreover, untenable conditions like low visibility due to an accidental fire or missile impact can be introduced in order to establish the Available Safe Egress Time and compare it with the T_{ET} obtained.

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