NATIONAL TECHNICAL UNIVERSITY OF ATHENS

School of Naval Architecture & Marine Engineering

Division of Ship Design and Maritime Transport

Diploma Thesis

“Sensitivity analysis of passenger evacuation time using numerical simulations”

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Ευχαριστίες

Με το πέρας της διπλωματικής αυτής εργασίας, ολοκληρώνεται και η διαδρομή μου ως προπτυχιακός φοιτητής της Σχολή Ναυπηγών Μηχανολόγων Μηχανικών του Εθνικού Μετσοβιου Πολυτεχνείου. Θα ήθελα να ευχαριστήσω μια σειρά ατόμων αφ’ενός για την εκπόνηση της παρούσας εργασίας, και αφ’ετέρου για την ολοκλήρωση του ταξιδιού μου ως φοιτητής.

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Η διπλωματική αυτή εργασία είναι αφιερωμένη στη γιαγιά μου, Κλειώ.

Contents

Περίληψη

Η παρούσα διπλωματική αποσκοπεί στην ανάλυση της ευαισθησίας του χρόνου εκκένωσης σε επιβατηγό πλοίο ως προς κάποιες βασικές παραμέτρους, χρησιμοποιώντας αριθμητικές προσομοιώσεις. Η υλοποίηση αυτού γίνεται μεσώ του pathfinder, ενός λογισμικού προσομοίωσης. Επιπλέον, η ανάλυση αυτή εμβαθύνει στον υπολογισμό του βαθμού επιρροής που ασκούν οι βασικές αυτές παράμετροι στον τελικό χρόνο εκκένωσης με μετρό σύγκρισης ένα βασικό σενάριο το οποίο υιοθετείται ως ονομαστικό.

Ξεκινώντας, γίνεται σύντομη ανάλυση των ναυτικών ατυχημάτων περιγράφοντας την σταδιακή βελτίωση της ασφάλειας στη θάλασσα, με το πέρας του χρόνου, ενώ σχολιάζονται και κάποια πρόσφατα σοβαρά ατυχήματα ως προς την ανταπόκριση τους στις προσδοκίες των ισχυόντων κανονισμών.

Στη συνεχεία παρουσιάζεται εκτενώς το κανονιστικό πλαίσιο που άφορα στις διαδικασίες εκκένωσης πλοίου, δίνοντας ιδιαίτερη έμφαση στις οδηγίες του παγκοσμίου οργανισμού ναυτιλίας (IMO) σχετικά με την ανάλυση διαφυγής στο πλοίο. Η ανάλυση περιλαμβάνει και την περιγραφή των μεθόδων που ακολουθούνται για τη διαδικασία προσομοιώσεων που απαιτούνται με σκοπό τον υπολογισμό χρόνων εκκένωσης σε ενδεχόμενα σενάρια. Οδηγία πάνω στην οποία βασίζεται και η κυρία ανάλυση της εργασίας.

Έπεται η ανάλυση του προγράμματος προσομοίωσης pathfinder. Όλα τα απαιτούμενα χαρακτηριστικά και οι πιθανοθεωρητικες παράμετροι που υπεισέρχονται στις διαδικασίες περιγράφονται με σαφήνεια, όπως η συμπεριφορά, η ταχύτητα και οι χρόνοι απόκρισης των επιβατών.

Καταλήγουμε έτσι στο βασικό μοντέλο των καταστρωμάτων καμπίνων ενός πλοίου που πρόκειται να αναλυθεί η ευαισθησία του χρόνου εκκένωσης του. Κατ’αρχας, βασικός λόγος της επιλογής των χώρων αυτών είναι πως η εργασία αυτή άφορα άμεσα στην ασφάλεια της ανθρωπινής ζωής, όποτε και επικεντρώνεται στα σημεία υψίστης σημασίας αυτής, μιας και συγκεντρωνεται το μεγαλύτερο ποσοστό ανθρώπων σε αυτά.

Έτσι, η ανάλυση ξεκινάει με βάση ένα φυσιολογικό σενάριο, πάνω στο οποίο διαφοροποιείται κάθε φορά μια παράμετρος αυτού. Πιο συγκεκριμένα, οι παραμετροι αφορούν στην ύπαρξη κλίσης, πανικού, περιορισμένης ορατότητας και μειωμένων εξόδων. Ακολουθεί λεπτομερής σύγκριση και σχολιασμός των αποτελεσμάτων των ποικίλων αυτών προσομοιώσεων εκκένωσης σε σχέση με το ονομαστικό σενάριο σε επίπεδο χρόνου, ρυθμού πλήρωσης εκκένωσης και επίπεδων συνωστισμού. Επιπλέον, όμως, λαμβάνονται και ορισμένα συνδυαστικά σενάρια, που περιλαμβάνουν παραπάνω από μια εκ των διαφοροποιημένων παραμέτρων, ώστε να εξεταστεί αν η από κοινού τους επίδραση είναι αθροιστική.

Προκύπτουν κατ’ αυτόν τον τρόπο σημαντικά αποτελέσματα των βαθμών απόκλισης και κατ επέκταση επιρροής του χρόνου εκκένωσης, αναδεικνύοντας την ευαισθησία του χρόνου

εκκένωσης στις εκάστοτε μεταβολές συνθηκών που μελετήθηκαν.

Καταληκτικά, παρατίθενται τα συνολικά συμπεράσματα που εξήχθησαν από το σύνολο της εργασίας, με αναφορά των παραδοχών που θεωρήθηκαν για την εκπόνηση της ανάλυσης, και την ανασκόπηση των ευρυματων με την ουσιαστικής σημασίας τους.

Η διαδικασία των προσομοιώσεων και της σύγκρισης τους προσφέρει την δυνατότητα στον μελετητή να εξετάσει τις διάφορες των χρόνων εκκένωσης και άλλων ιδιοτήτων των διάφορων σεναρίων και να εντοπίσει ευάλωτα σημεία εκκένωσης και περιοχές υψηλού συνωστισμού. Συμβάλλει λοιπόν σημαντικά στην μελέτη βελτίωσης σχεδιασμού πλοίου για περαιτέρω αναβάθμιση των σχεδίων εκκένωσης και κατ΄΄επεκταση στην ασφάλεια που αυτό παρέχει.

Abstract

The purpose of this thesis is to analyze the sensitivity of the evacuation time of a passenger ship in basic parameters using numerical simulations through a software for their implementation and also to calculate the degree of influence these parameters have on the evacuation time of a basic scenario that is considered as the nominal one.

Initially, the regulatory framework for the evacuation process is presented and specifically the detailed guidelines of IMO related to the evacuation analysis are described in detail.

Then, the simulation software is analyzed by describing the probabilistic parameters involved in the process such as the behavior and speed of the passengers, their response time, etc.

The main model of the scenarios to be simulated is on the cabin decks of a cruise ship. The foremost reason for this choice is that the study concerns the safety of human life, so it focuses on the points that are considered of utmost importance to it, as they include the greater percentage of human life on board. So, based on a basic normal scenario, we simulate other scenarios by diversifying each time some of the parameters. Comparing the evacuation results of those simulations to the nominal scenario, the sensitivity of the evacuation time in different situations is finally figured out.

The process of simulations and their comparison offers the feasibility for the researcher to examine the differences in the evacuation times of the scenarios and to locate the 'weak' evacuation points and the highly-congested areas; a significant contribution to the study of the ship design improvement to further upgrade its evacuation plan and hence the safety it provides.

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1 Introduction

1.1 Preview

The fundamental purpose of a ship is transportation of humans, goods and services. Recently, there has been a massive increase in the number of passenger ships but also in their size. The accommodation and entertainment of significantly increased passengers in cruise ships caused a raising demand for more decks and even larger ship design. A need, to seek for innovative solutions to improve further the safety and emergency situation responses on board occurs. However, the stipulation of safety standards is of utmost importance and is made by the assumption that absolute safety cannot exist in reality. The mathematical definition of safety is generally described as a situation in which the extent of risk is at acceptable levels (Spyrou, 2017).

Until the end of the 19 th century, sole priority was the transportation of cargo or services to the desired destination with the resulting in increasing frequency of accidents with catastrophic consequences. In case of accident, there were no deterrent or response plans and so any unexpected incident; that nowadays would have been rapidly resolved, could potentially cause severe human and environmental ramifications.

The problem was becoming more complex about passenger ships, with regard to the very important sector of the evacuation of the ship and the adequacy of the rescue equipment in case of accident, which endangered human life. The layout and design of the spaces were not derived from a detailed analysis of an evacuation plan in case of accident, resulting in a lengthy and unsuccessful evacuation of the ship, which in numerous cases would be fatal for many humans' lives.

IMO is progressively developing the crucial part of ship evacuation and its optimization as much as possible, incorporating regulations and rules; based on past experience of marine disasters and the state-of-the-art know-how. This process keeps on, as far as such accidents happen and evacuation times are not the desired and calculated ones.

Lately, the effort for full compliance of the ships and the crews to IMO regulations is increasing, to limit the evacuation time error to simulation matters. Measures regarding the ship's construction, fire protection-detection-extinction, life-saving equipment, helicopter landing & pick-up area and crew training.

The simulation of evacuation of a ship in case of emergency, because of a fire, large-scale influx of water due to collision or grounding, equipment failure or human error, especially of a passenger ship, is of utmost importance for human life safety. In order naval architects to be able to improve the arrangements for the layout of the superstructures of the ship, so that to it is more efficiently evacuated. Special reference to passenger ships is made, due to the huge number of humans' lives carrying; as well as the existence of many decks and their complicated interior design and geometry.

The tragedy of the ESTONIA Ro-Ro passenger vessel that stressed the necessity of more rational arrangements that would enable a safer and easier evacuation of ships in emergencies. In addition to this, accidents such as the Costa Concordia landing and the MS Norman Atlantic fire case, create pressure to optimize the process of ship evacuation.

However, ship evacuation is a process involving procedural and environmental factors as well as human behavior that in many cases make conventional evacuation software for different fields of use unsuitable for simulated evacuation to a ship (Stefanidis, et al., 2020).

Such factor that cannot be predicted sufficiently is the human behavior under stress and when in groups of large number of people. There are situations where behavior becomes irrational. This is usually described by the term 'panic'. (Papanikolaou & Boulougouris, 2002). In addition, other important factors such as the inclination of the ship or the unavailability of a number of exits impact the evacuation process & duration, and are about to be analysed in this thesis.

1.2 **Literature Review**

Researches, analyses and studies have been conducted before, gave the necessary tools to make the current thesis happen. The following thesis and papers are the main ones that contributed to accomplish this project.

Papadakis (2020) in his thesis with title "Examination of uncertainties in simulation of evacuation of passenger ships", analyses characteristics of a numerical code by emphasizing the probabilistic parameters involved in the evacuation process such as the response time and the movement speed of passengers. Basic IMO scenarios with both public spaces and cabin areas are involved in the simulations; by the changing of the availability of exit doors in each deck, important conclusions are made. Comparing those simulations with different configurations, enables to check differences in evacuation times of scenarios and identify areas of increased congestion from passengers.

Kotsakis (2021) in his thesis "Development of code for modelling the evacuation process on a cruise ship" contributes as for the variables which examine the sensitivity of evacuation times, and are analyzed in Chapter 8 of his thesis, is decisive. Using the Python programming language translates the effect of these variables into passenger movement speeds during evacuation, which is used exactly as a n input for the current thesis' simulations. Specifically, the variables analyzed are:

- Ship movement and inclination
- Visibility
- Movement Speed on stairs
- Selection of exit
- Behavior in emergency and panic situations

In the paper of Themelis et al. (2012) several fire simulations into a notional cruise ship are carried out, based on scenarios. In each of those, conditions, such as visibility loss and toxic incapacitation, were examined as for their impact to the evacuation. The second part of the paper emphasizes the uncertainties affiliated with the proper setting of safety norms. Conclusively, specific qualitative reduction of the visibility norm, increases the estimated critical time.

Sun et al. (2017) in their study “An Experimental Study on Individual Walking Speed during Ship Evacuation with the Combined Effect of Heeling and Trim” developed a ship corridor simulator to examine the effect of ship heeling and trimming on the movement speed of passengers. The simulations that have been carried out, tested several angle values, to facilitate different conditions during the evacuation process. The results provided substantial knowledge for the sensitivity analysis of this study.

Helbing, D. and Johansson, A. (2014) in their article “Pedestrian, Crowd, and Evacuation Dynamics” describe efforts to model the behavior of individual pedestrians and their interactions in crowds, which generate certain kinds of self-organized patterns of motion. Moreover, this article focusses on the dynamics of crowds in panic or evacuation situations, contributing to the creation of a passenger in panic profile.

Koromila et al. (2020) encourage the development of alternative ship designs using performance-based assessment procedures. The aim of the paper is to examine how the setting of the various human safety thresholds occuring in the criteria can affect the depiction of the fire safety level of a design. These criteria refer to the minimum required visibility, and the maximum required temperature and concentration of toxic substances, principally; so that occupants can safely evacuate the area affected by fire effluents. Thus, a series of fire and evacuation simulations were carried out in order to evaluate the losses emanating from systematically produced fire incidents. In other words, those simulations shall produce the necessary data for the assessment of the IMO tenability criteria. In fact, the majority of losses during the simulations came from lack of visibility. Technology designed exceptionally for guidance onboard towards emergency exists may decisively affect the level of safety.

1.3 Aim of the study

Briefly, the current study is an attempt to approach the sensitivity levels of the evacuation time to the various special conditions that may exist during the process of escape. Ship evacuation is a huge chapter and the sensitivity analysis of the evacuation time to all the factors affecting it cannot be analyzed at once.

Before the implementation of the analysis, reference of the IMO regulatory framework for the evacuation process as well as the simulation of a series of tests that IMO has proposed in its guidelines in order to facilitate a realistic and representative analysis. Proceeding to the main analysis, where a basic scenario of a ship evacuation model is simulated, getting evacuation time, flow and completion rate outputs. Supposing this as the nominal scenario, four additional cases are set, based on the normal one, but each with a modified parameter. Specifically, ship heeling, reduced visibility of passengers, limited available exit doors and panic behavior of occupants are the cases that examine the level of influence they shall have on the evacuation aforementioned outputs, compared to the nominal one. In addition, for each modified parameter studied, different range values have been tested, to evaluate its influence on every form it may happen. The sensitivity analysis is completed after examining combined scenarios of the modified parameters, in order to figure out if the occurring results are a sum up of each individually.

Thence, this thesis is a valuable contributor for the researcher to deepen the impact extent of such factors and examine furthermore the sensitivity of evacuation time to them. In addition, it shall broaden the path for solutions that cope with the delays occurring by the studied factors, enhancing the human safety standards, that is the primary scope, eventually.

1.4 Structure of the thesis

The structure of this thesis has the following sequence:

In chapter 2, statistical data and fundamental definitions of marine casualties are presented, ending up with highlighting some recent major accidents.

Chapter 3, refers to the regulatory framework for evacuation process in passenger ships, analyzing all the codes and regulations relative to ship evacuation.

In Chapter 4, the 'Pathfinder' simulation software and its parameters and quantities that are necessary for the evacuation simulations are described in detail.

In chapter 5, tests provided by IMO are being verified and validated by the use of the pathfinder simulation software to confirm its credibility and precision.

Chapter 6, is the main analysis chapter, where it is described, initially, the process of creating the simulation model, and later the various scenarios used for the sensitivity analysis are carried out, with their different settings each, presenting and analyzing the results. Follows an aggregated Table of all the different simulation cases, comparing their evacuation data.

Finally, chapter 7 contains the conclusions of the thesis.

2 Maritime accidents analysis

IMO introduced to SOLAS the ‘Casualty Investigation Code’ IMO (2014). This code includes the relevant definitions and the main categories of Maritime Casualties. According to IMO, a Marine Casualty is any incident or sequence of incidents resulted in any of the following results, that took place in direct connection with the ship's operations (IMO, 2014):

- Death, serious injury or even loss of person on board.
- Loss, abandonment or material damage of a ship. Additionally, grounding, incapability of sailing or engaging in a collision.
- Serious damage or possibility of causing serious damage to the environment, caused by damage of one or more ships.
- Material damage to the external naval infrastructure of a ship, which could set the safety of the ship, another ship or a person in danger.

The categories of Marine Casualties are (IMO, 2014):

- Very Serious Casualty
- Serious Casualty
- Less serious marine casualties

Marine Incident: any incident or sequence of incidents, that occurred directly to the operations of a ship and either endangered or, if it was not corrected, would endanger the safety of a ship, its occupants or any other person or the environment. A chart of the severity of marine casualties and incidents is presented below, EMSA (2021):

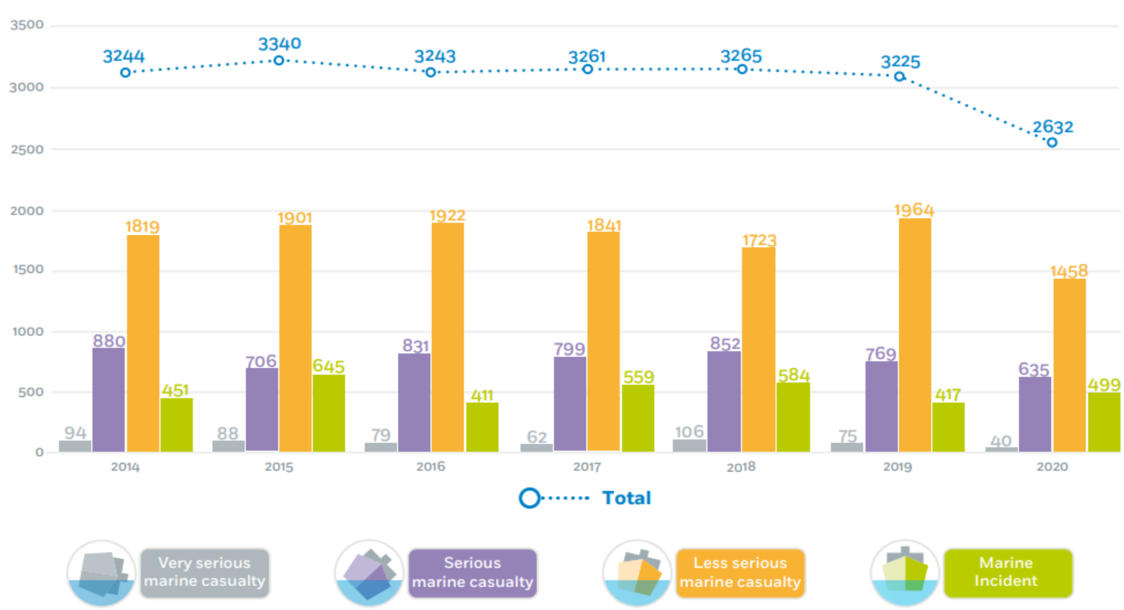


Figure 2.1: *Severity of marine casualties & incidents 2014-2020, EMSA (2021)*

As shown in Figure 2.1, 2020 was the first and lone year that casualties and incidents were significantly fewer (2632) compared to the more or less 3200 ones of all the previous years.

Marine accidents and especially incidents are very common in the shipping field, as they happen daily and are handled efficiently. The types of marine accidents are:

- **Collision:** Between two ships or even a ship and an object.
- **Grounding:** When the ship is attached to either an object or the seabed.
- **Contact:** When the ship collides with any floating or stable objects excluding those involved in collision or grounding accidents.
- **Foundering:** When load shift or water influx occurs, caused mainly by loading mistakes.
- **Fire/Explosion:** The cases where fire or explosion are the first events reported.
- **Equipment failure:** Includes mechanical installation, steering shaft and electronic installation failures
- **Hull damage:** Accidents related to hull failure, due to severe weather conditions.
- **Non-accidental structural failure (NASF):** When the hull is cracked and fractures, affecting the seaworthiness of the ship.

Among all of these types of marine casualties, collision and fire explosion events are considered to be the most frequent and, therefore, the most catastrophic when it comes to shipwrecks.

IMO sets a potential-loss-of-life (PLL) indicator (2.1) for the assessment of deaths, which is widely used in the statistical study and recording of marine casualties (IMO, 2007):

$$PLL = \frac{Number of Fatalities}{Shipyears} \quad (2.1)$$

Eliopoulou, Papanikolaou & Voulgarelis (2015) statistically analyse ship accidents that happened from 2000 to 2012. Reviewing the passenger vessels, Figure 2.2 below presents the fatalities per shipyear by -aforementioned accident category, specified for each three types of passenger ships.

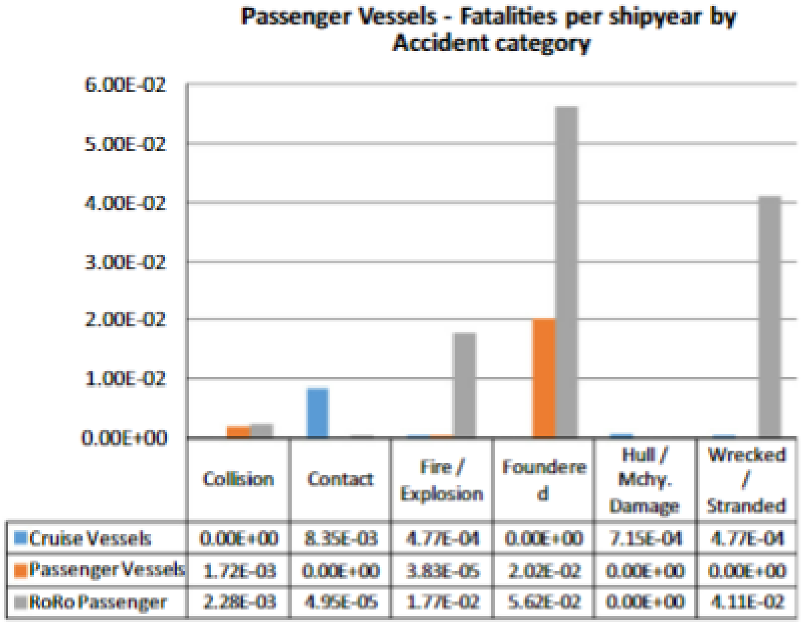


Figure 2.2: *PLL on passenger vessels (by accident category), Eliopoulou et al. (2015)*

It is apparent that Foundering, Wrecked/Stranded and Fire/Explosion are the top three types of accidents with the highest fatality frequency among the years on Passenger and passenger vessels, whereas on cruise vessels the contact is dominating.

Whereas, the accident frequency is defined as (IMO, 2007):

$$Frequency = \frac{Accidents}{Shipyears} \quad (2.2)$$

Where shipyears = ships on the market (by type) * years (on the study) [12 years in this case].

EMSA (2021), on the Figure 2.3 and Table 2.1 below presents the number of fatalities in passenger ships across 2014-2020, concluding that since 2016 the number of fatalities on board of passenger vessels steadily decreased. In addition, the number of victims was almost equal among passengers and crew members on board.

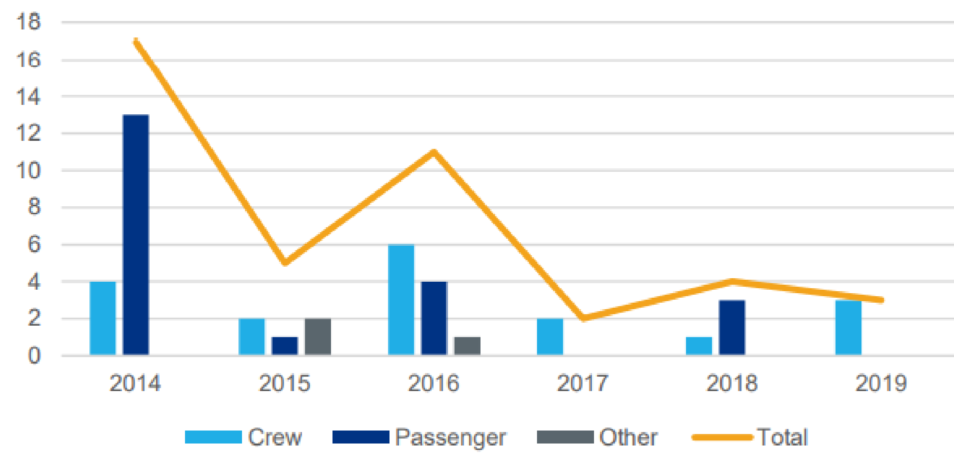


Figure 2.3: Number of fatalities in passenger ships 2014-2020 (by on-board role categories), EMSA (2021)

	2014	2015	2016	2017	2018	2019	Total
Crew	4	2	6	2	1	3	18
Passenger	13	1	4	0	3	0	21
Other	0	2	1	0	0	0	3
Total	17	5	11	2	4	3	42

Table 2.1: Number of fatalities in passenger ships 2014-2020 (by on-board role categories), EMSA (2021)

Table 2.2 and Figure 2.4 present 10 recent major accidents, their evacuation time and deaths. In some cases, evacuation was considered timely and effective with durations complying with IMO guidelines (MSC.1/Circ.1533), but in some others evacuation times are considered as prohibitive.

Passenger Ship Names	Evacuation Time (Hrs)	Deaths
Explorer (Antarctica, 2007)	3	0
Lisco Gloria (Germany, 2010)	4	0
Costa Concordia (Italy, 2012)	6	32
Norman Atlantic (Italy,2014)	24	19
Sea Diamond (Greece, 2007)	3.5	2
Jalakanyaka (India, 2009)	7	45
Sewol (Korea, 2014)	2	304
Samina (Greece,2000)	1	81
Viking Sky (Norway, 2019)	40	0
Queen of the North (Canada, 2006)	0.5	2

Table 2.2: Evacuation time and deaths of Ten (10) recent major accidents

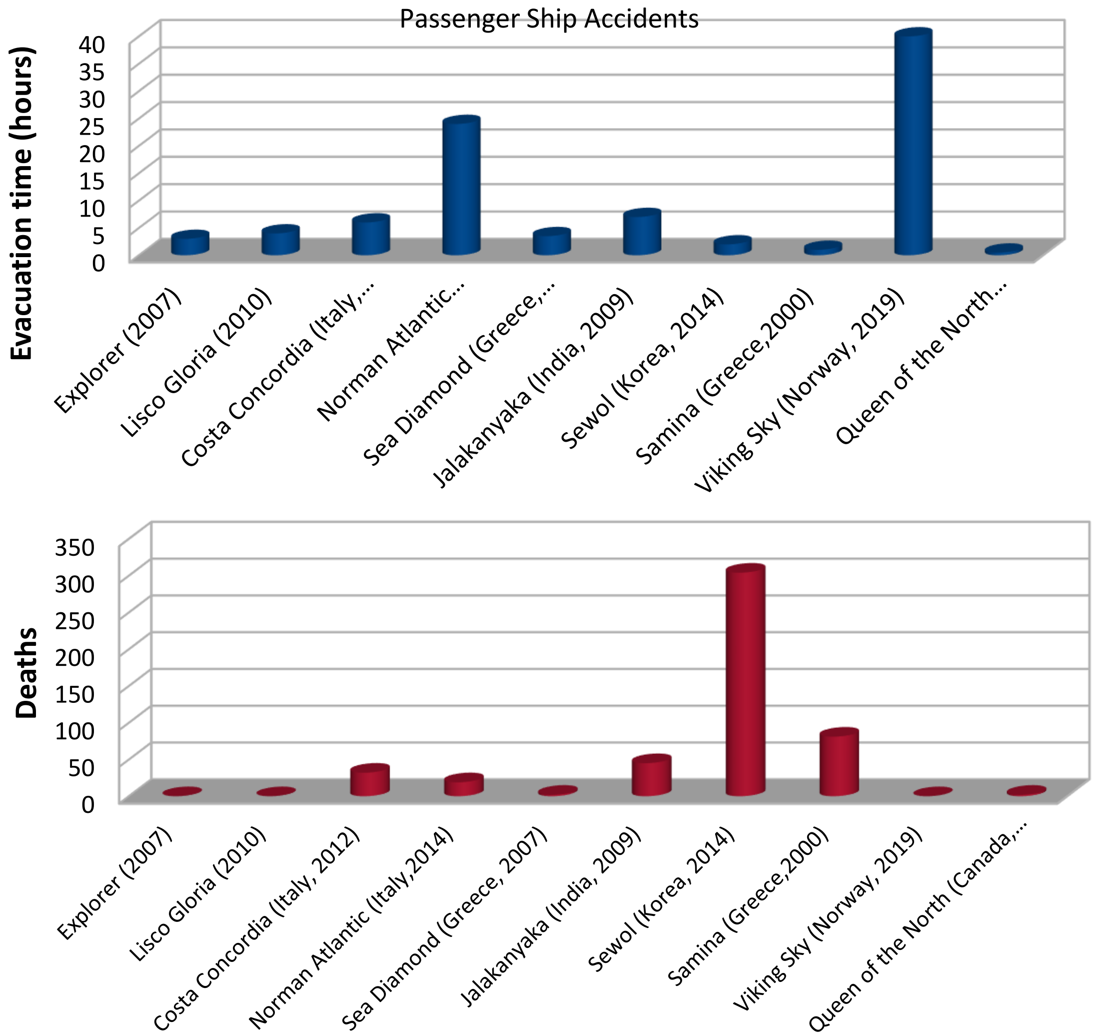


Figure 2.4: Evacuation time and deaths of 10 recent major accidents

3 Regulatory Framework for Evacuation Process in Passenger Ships

3.1 The Passenger Ship

The high level and safety standards of passenger ships play a vital role, given the numerous lives they carry and that it is very difficult to predict uncertain human behavior in emergency situations (Lee et al., 2003).

Defining the passenger ship: is a ship deemed suitable for carrying 12 passengers and more (IMO, 2019).

A few requirements during a ships's construction (or conversion), deem it as an appropriate passenger one, its watertight subdivision, the type and adequacy of rescue and fire-fighting equipment, and an effective evacuation plan. All the above may modify, depending on the area of the ship's operation and its number of passengers,

The speed of modern passenger ships holds a range from 17 to 30 knots with an average of 20 knots, depending on the type of passenger ship. The feature of a passenger ship is its Gross Tonnage (GT).

Passenger ships are, generally, divided into the following main categories:

I. Ro-Ro Passenger Ships (ROPAX): Ships carrying people and vehicles (cars, trucks, machines).

II. Cruise ships: The large recreational boats that travel around the world and are divided into additional categories according to their size (Small up to 800 passengers, Medium 800-2500, Large 2500 and above).

III. High-speed Passenger Ships: This category includes all passenger-cargo vessels (Trans-Oceanic, Local Vessels, Coastal) and mixed passenger-cargo vessels (Freighter Travel Ship).

3.2 SOLAS Convention

SOLAS convention is the result of an international conference that took place after the sinking of the Titanic, and was approved in 1914, but it never came into force due to the First World War. Four revisions of the convention followed, in 1929, 1948, 1960, and finally in 1974. Last one was the overall review which came into force in 1980 and is still in force with 164 States parties. Modifications and updates onto it continue to reflect today's demands. The main objective of the Convention is to define the minimum limits for the construction, equipment and operation of ships which should be harmonized with safety from the perspective of human life. The recently renewed (2020) SOLAS International Convention consists of 14 Chapters, so far, each of which concerns a maritime safety issues agenda IMO (2019). It also contains 8 codes including the Code for the detailed calculation of evacuation time in Chapter II-2.

Figure 3.1: SOLAS CHAPTERS (Marine Insight, 2021)

The most important resolutions and guidelines on the evacuation procedure in passenger ships are (IMO, 2019):

- SOLAS Chapter II-2: This chapter provides some guidance on alarm systems, design constraints and arrangement of the inside ship areas participating in the evacuation process.
- Chapter 13 of Fire Safety Systems (FSS Code): which is found in Chapter II-2 of SOLAS, provides detailed instructions on the dimensioning of runways, steps and doors. A key factor in dimensional calculations is the number of people, in case of danger, who will be required to serve this escape mean.
- Resolution MSC.1/Circ.1238 (IMO, 2007): adopted by IMO in 2007, sets out an indicative method for calculating the evacuation time of a passenger ship (simple and complex method). This guideline incorporates the 3 previous ones and applies to cruise ships, Ro-Ro passenger ships, and high-speed passenger ships.

  This Guideline is related to Regulation 13/7.2 in Part D of Chapter II-2 of SOLAS, mentioning the mandatory early stage analysis of Ro-Ro vessels and the optional analysis of other passenger ships.
- Updated Resolution MSC.1/Circ.1533 (IMO, 2016): Adopted in 2016, indicates method for calculating evacuation time, which was created alongside with the regulation that entered into force in SOLAS (2020) and applies to all passenger ships. That regulation states that all passenger ships carrying 36 passengers or more require the application of an evacuation analysis in its early stages of design.
- LSA Code: adopted in 1996, provides international requirements for the life-saving appliances including personal life-saving appliances, visual aids, survival craft launching and embarkation appliances and marine evacuation systems; line throwing appliances; and general alarm and public address systems.

3.2.1 SOLAS Chapter II-2

It focuses on the escape of the seafarers or passengers in case of fire or any other emergency. It provides the means and the measures to be taken to protect against fire in areas accommodation, cargo and machinery spaces for different types of ships. The regulations of this chapter include the following principles:

- Division of the ship into main vertical zones (MVZ).
- Separation of accommodation spaces from the rest of the ship by heat and structural limits.
- Protection of runways and access passages for the fire-fighting.
- Immediate availability of fire-fighting systems.
- Regulations also require at least two different ways of escape of each main zone, one of them must end up in stairway for vertical evacuation.

Amendments to SOLAS II-2/13 made Evacuation analysis now as mandatory.

Existing paragraph II-2/13.7.4 is now deleted. New paragraphs II-2/13.2.7.1 and II-2/13.2.7.2 have been introduced which require escape routes to be evaluated to demonstrate that the ship can be evacuated in the required time. According to MSC.404(96), the evacuation simulation will be used to identify and eliminate congestion which may develop during abandonment and demonstrate that escape arrangements are sufficiently flexible to provide for the possibility that certain routes/areas may not be available as a result of a casualty. (IMO 2020)

3.2.2 Fire Safety Systems (FSS Code)

FSS Code is one of the most important regulations regarding fire safety systems on board. Its regulations based on SOLAS 1974 Convention are mandatory for fire safety and are required by Chapter 2 of the International Convention. It is consisted of 15 chapters, of which only chapter 13 concerns directly the evacuation process.

Chapter 13 'Arrangement of means of escape' contains a very important regulation on an effective evacuation plan. This regulation contains detailed instructions on the dimensioning of the means of escape (stairways, corridors and doors). Those ones shall be determined by the number of persons to be used. The calculations of the minimum requirements of the above are made according to two cases of distribution of persons involved in the evacuation process, that are described at MSC.1/Circ.1533 detailed.

3.2.3 Resolution MSC.1/Circ.1238

At the beginning of the 21st century the SOLAS Convention required the analysis of the process of evacuation of a passenger Ro-Ro ship simultaneously with the design and layout of its interior spaces. Thus, IMO introduced Resolution MSC.1/Circ. 1033 and later MSC.1/Circ. 1238 'Guidelines for development analysis for newbuilt and existing passenger ships' focusing on carrying out an efficient analysis on Ro-Ro and other passenger ships. Therefore, SOLAS required that Ro-Ro passenger ships must be definitely compliant with this Resolution and evacuation analysis on other passenger ships could be optional during their lifetime, if required.

3.2.4 Updated: Resolution MSC.1/Circ.1533 and Reg. II-2/13.3.2.7

In 2016, IMO published the above Regulation concerning all passenger ships and has been implemented since January 2020, in accordance with the Resolution MSC.1/Circ.1533, which replaces the latter MSC.1/Circ.1238. The Regulation now requires a detailed evacuation analysis, on passenger ships carrying 36 or more passengers, from their initial design stages.

At its 96th Conference, Maritime Safety Committee adopted the revised Resolution MSC.1/Circ.1533 for the evacuation analysis for new and existing passenger ships, setting them as guideline for the application of the Regulation II-2/13.3.2.7 of SOLAS. Thus, evacuation analysis becomes imperative not only for Ro-Ro vessels, but also for other species built after the 1st of January 2020 (MSC.1/Circ.1533). There have been proposed two cases for the evacuation process, on which the distribution of persons is described as below:

- ➔ <u>Case 1 'Night Scenario':</u>
    - ◆ All Passengers are in their cabins with maximum capacity
    - ◆ ${}^{2}/_{3}$ of the total crew is in their cabins
    - ◆ ${}^{1}/_{3}$ of the total crew is distributed as followed:
        - ½ is located in the service spaces
        - ¼ is located at their emergency stations
        - ¼ is initially located at the assembly stations

- ➔ <u>Case 2 'Day Scenario':</u>
    - ◆ All Passengers are in public spaces occupying 3/4 of the total space capacity
    - ◆ ${}^{1}/_{3}$of the total crew is in the crew accommodation spaces
    - ◆ ${}^{1}/_{3}$ of the total crew is in public spaces,
    - ◆ ${}^{1}/_{3}$ of the total of crew is distributed as followed:
        - ½ is located in the service spaces
        - ¼ is located at their emergency duty locations
        - ¼ is initially located at the assembly stations

<u>Cases specifications:</u>

The MSC.1/Circ.1533 suggests to include in the evacuation analysis at least four scenarios, which are characterized by different distributions and features of persons (both passengers and crew):

- **Case 1 (primary night evacuation case)**: persons are distributed exactly as described in 'night scenario'.
- **Case 2 (primary day evacuation case)**: persons are distributed exactly as described in 'day scenario'.
- **Case 3 (secondary night evacuation case)**: persons are distributed as in "night scenario".

  Only the MVZ generating the longest assembly duration is further investigated according with one of the following alternatives (Alternative 1 is recommended):

    - Alternative 1: a main escape route previously used in the considered MVZ is unavailable for the simulation
    - Alternative 2: 50% of persons of the most populated adjacent MVZ is forced to move into the considered MVZ

- **Case 4** (**secondary day evacuation case)**: persons are distributed as in "day scenario", while evacuation scenario is exactly as 'Case 3'.

Scenarios 1 and 2 are the main scenarios used both in the IMO proposed analytical methodologies and in the various evacuation models, whereas Cases 3 and 4 are secondary and will not be included in the simulations of the present thesis.

The resolution consists of three annexes:

- **Annex 1:** Guidelines for a simplified evacuation analysis for new and existing passenger ships (simplified method of IMO).
- **Annex 2:** Guidelines for an advanced evacuation analysis of new and existing passenger ships (advanced method of IMO).
- **Annex 3:** Guidance on validation/verification of evacuation simulation tools.

The first two annexes are proposed methodologies by the IMO.

Two methodologies are proposed: a simplified and an advanced. The simplified method is less realistic but can be used in the early stages of the ship's design for initial assessment of the efficiency of the life-saving equipment. In larger and more complex ship’s interior layout, the advanced method is recommended.

These proposed methodologies have been extensively criticized in the relevant literature for three main reasons:

- Ignores the inclination and movement of the ship in case of collision and water inflow, as well as the various environmental factors (e.g. limited visibility and toxic releases in the event of fire).
- Ignores the psychological factors (e.g. panic fear, team building) that significantly influence passengers' decisions.
- The alternative routes that passengers can take in case their using main route is either blocked for some reason (e.g. fire) or the congestion on it is much.

The third annex includes several tests that have to successfully check the various computer escape models in order to adequately describe the process.

Before describing the two methods, some of the basic features associated with the evacuation of the ship shall be mentioned, as described in Annex 1 of the Resolution.

Total evacuation time

The total evacuation duration is divided into four time periods:

I. **Response duration (R):** the effective reaction time to an emergency situation. This duration begins upon initial notification of the emergency (usually an alarm) and ends when the passenger realizes the situation and starts to move toward the assembly station.

    - Simplified method: day scenarios: R= 5 min equal for each person
      night scenarios: R=10 min equal for each person
    - Advanced method: R is defined by log-normal distribution

II. **Travel duration (T):** the time spent to move all the persons on board from the place occupied upon the emergency notification to the assembly stations.

III. **Embarkation duration (E):** the time of embarkation on lifeboats

IV. **Launch duration (L):** the launch time of the lifeboats

According to IMO methodologies:

- R + T (simplified method) are defined as 'Mustering time'.
  or T (advanced method)
- E + L is defined as 'Abandonment time'.
- Their sum is defined as 'Evacuation time'.

Equations 3.1 and 3.2 are used to compute the total evacuation time:

➔ $1.25 \cdot (R+T) + {}^{2}/_{3} \cdot (E+L) \leq n$ (3.1) (simplified method)

➔ $1.25 \cdot T + {}^{2}/_{3} \cdot (E+L) \leq n$ (3.2) (advanced method)

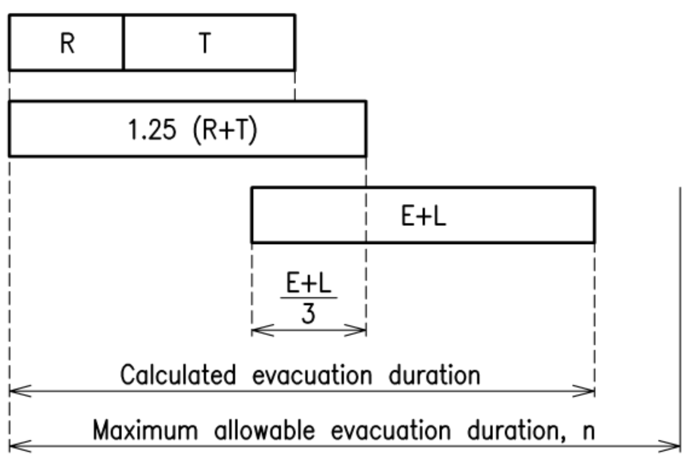


Figure 3.2: Evacuation Time (MSC.1/Circ.1533)

The decimal 1.25 is the safety factor added to counteract the various simplifications of the method. The fraction 2/3 is introduced into the total time calculation as the first phase T of the process overlaps with the second phase (E+L).

n is the allowable duration and takes the values:

- 60 min, for Ro-Ro vessels.
- 60 min, for every other passenger ship, with no more than 3 main vertical zones.
- 80 min, for every other passenger ship, with more than 3 main vertical zones.

The time (E+L) shall not exceed 30 minutes. Thus, it can be taken as 30 min, if no data are available from similar passenger ships.

(i.e. ${}^{2}/_{3} \cdot (E + L)$= 20min)

The total times: n, E+L are indicative times of the IMO instructions and are considered in case of unavailability of statistical data by similar ships or data provided by the manufacturer

Regarding the advanced method, the total time to reach the concentration stations T ('mustering time') given the time E+L (30 minutes) and the evacuation time equation should be:

$1.25 \cdot T \leqslant 40min \Rrightarrow T \leq 32min$, for ships with 3 or less vertical zones.

$1.25 \cdot T \leqslant 60min \Rrightarrow T \leq 48min$, for ships with 4 or more vertical zones.

Response duration (R):

As defined above, the reaction time to an emergency situation has been analyzed for the benchmark scenarios of day and night. Those response time distributions follow the 3.3 and 3.4 log-normal distributions, as shown in Figures 3.3 and 3.4:

For cases 2 and 4 (day cases):

$$y = \frac{1.00808}{\sqrt{2\pi}0.94x} exp\left[\frac{-(ln(x)-3.44)^2}{2\times0.94^2}\right], \qquad 0 < x < 300 \text{ (s)} \quad (3.3)$$

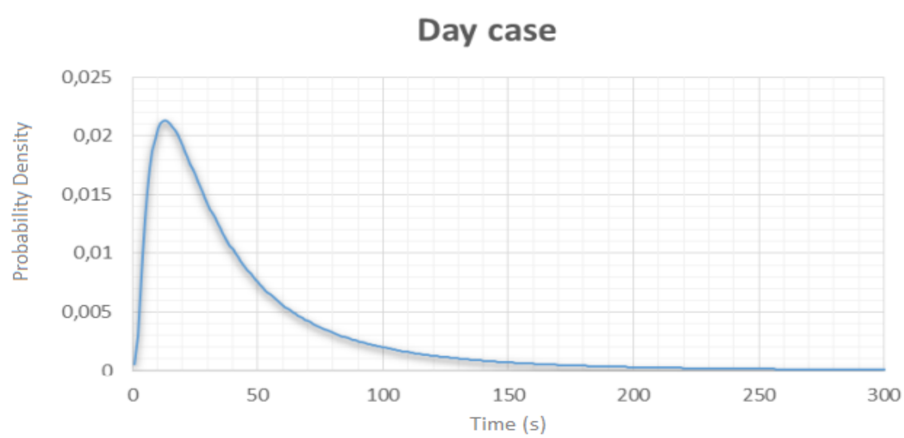


Figure 3.3: Distribution (probability density function) of initial delay for day case

For cases 1 and 3 (night cases):

$$y = \frac{1.011975}{\sqrt{2\pi}0.84(x-400)} exp\left[\frac{-(ln(x-400)-3.95)^2}{2\times0.84^2}\right], \qquad 400 < x < 700 \text{ (s)} \qquad (3.4)$$

Where x is the delay duration in sec. and y is the probability density function of the x delay.

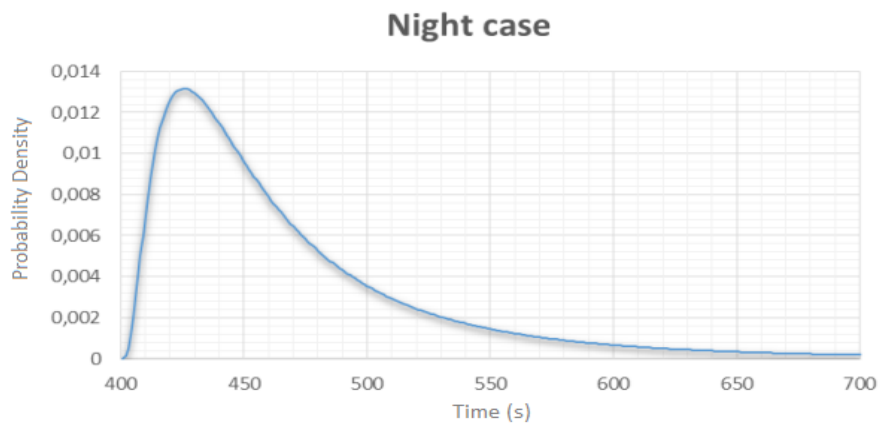


Figure 3.4: Distribution (probability density function) of initial delay for night case

Table 3.1 presents the response times in all day and night cases:

	Minimum (s)	Average (s)	Maximum (s)
Case 2 (day)	210	300	390
Case 4 (day)	210	300	390
Case 1 (night)	420	600	780
Case 4 (night)	420	600	780

Table 3.1: Population's response time in day & night cases (MSC.1/Circ.1533)

Simplified method of IMO

Assumptions

The simplified method of calculating the evacuation time is based on the following assumptions:

- Passengers and crew start moving at the same time to the escape exits and response time (R) is taken 5 min for day and 10 min for night scenarios.
- people move unhindered and there is no overtaking among them.
- the walking speed depends on the density of the people,
- Flow of people exists only towards emergency exits or assembly stations and reverse flow is calculated by a corrective factor.

Calculation of the 'Travel duration' (T)

In order to calculate the travel duration (T), the calculation of the maximum travel duration in ideal conditions (t_I) needs to be performed first. The existing model can be seen as a hydraulic network, in which the pipes are the corridors and the stairs, the valves are the doors and the tanks are the spaces where the passengers start.

The quantities to be calculated first:

- Density **D** (pers/m^2) of the persons per unit area of the runway.
- Initial specific flow **F_S** (pers/m/sec) by linear interpolation from existing table
- Flow the different means of escape **F_C** (pers/sec): the product of flow F_S times the clear width of the different means of escape W_C (m) (e.g doors and corridors)

  $Fc = Fs \cdot Wc$ (3.5)

Points on the path, where width is changed, or paths either merge or split (transition points), assume that the total input flows equal the total output ones.

$$\sum^{i}(in) = \sum^{j}(out) \qquad (3.6)$$

I. **Flow duration (t_F):** is the total time needed for N persons (passengers and crew) to move past a point in the egress system and it is given by the following formula: $t_F = \frac{N}{Fc}$

II. **Deck travel duration (t_{deck}):** The required time to move from the farthest point of the escape route of a deck to the stairway.

III. **Stairway travel duration (t_{stair}):** The time required to travel the stairway.

IV. **Assembly travel duration ($t_{assembly}$):** The time required to move from the end of the stairway to the entrance of the assigned assembly station.

V. The **highest travel duration in ideal condition (t_I):** Occurs as:

$$t_I = t_F + t_{deck} + t_{stair} + t_{assembly} \text{ (sec)} \qquad (3.7)$$

In order to exceed the limits of the hydraulic similarity, two corrective factors (γ & δ) are introduced, so that the travel duration (T) of a specific Case is given by 3.8:

$$T = (\gamma + \delta) \cdot t_I \qquad (3.8)$$

γ : equals to: 2 for primary evacuation cases (1& 2)

1.3 for secondary evacuation cases (3 & 4)

δ : (counter-flow correction factor) equals to 0.3 for all cases

Part of the evacuation analysis is also the identification of congestion points. Such points are:

- ➔ Spaces, where the initial density is higher than 3.5 pers/m^2.
- ➔ Locations, where the difference between the inlet and outlet calculated flow (F_c) is more than 1.5 pers/sec.

Advanced method of IMO

This method of evacuation analysis is performed with a specific software based on virtual reality; focusing on the calculation of the total evacuation duration, as well. However, the main difference is that all persons on board are represented as individuals, with particular traits. Some crucial features of this method are:

- ◆ Passengers and crew are represented as different units with singular abilities
- ◆ The distribution and number of passengers is based on the FSS Code
- ◆ The response durations (R) of the individuals are different and follow a log-normal distribution
- ◆ Persons have different movement speed, depending on sex, age and movement abilities
- ◆ Movement in groups is not taken into account
- ◆ Inclination and movement of the ship are not taken into account
- ◆ A corrective factor of 1.25 is used in the calculations due to the assumptions

The persons are divided into 12 categories, based on:

- sex
    - men
    - women
- age
    - at less than 30 years of age
    - between 30 and 50 years of age
    - over 50 years of age
- physical ability
    - fully capable
    - mobility impaired category 1
    - mobility impaired category 2
- on-board role
    - passengers
    - crew

Table 3.2 shows the population's composition*:*

Population groups – passengers	Percentage of passengers (%)
Females younger than 30 years	7
Females 30-50 years old	7
Females older than 50 years	16
Females older than 50, mobility impaired (1)	10
Females older than 50, mobility impaired (2)	10
Males younger than 30 years	7
Males 30-50 years old	7
Males older than 50 years	16
Males older than 50, mobility impaired (1)	10
Males older than 50, mobility impaired (2)	10
Population groups – crew	**Percentage of crew (%)**
Crew females	50
Crew males	50

Table 3.2: Population's composition (by age & gender) (MSC.1/Circ.1533)

IMO distributions include the movement speed of persons. The maximum unobstructed motions are those deriving from data published by Ando (1988) as a function of age. These are distributed according to the Figure 3.5 below.

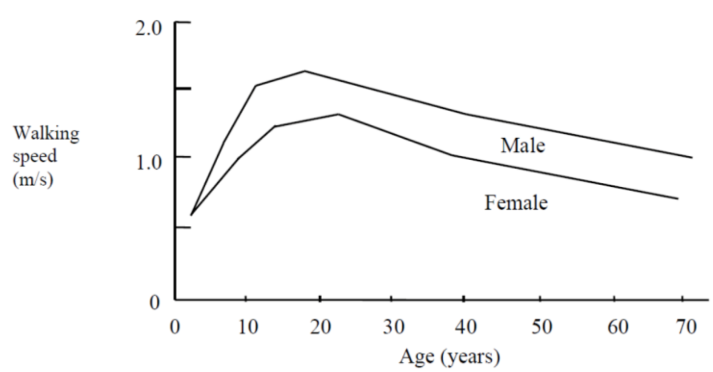


Figure 3.5: Speeds of individuals as a function of gender and age, (MSC.1/Circ.1533)

The walking speed of the passengers are presented by age and gender for each category for flat terrain and stairs, in Tables 3.3 and 3.4, respectively:

Population groups – passengers	Walking speed on flat terrain (e.g. corridors)	
	Minimum (m/s)	Maximum (m/s)
Females younger than 30 years	0.93	1.55
Females 30-50 years old	0.71	1.19
Females older than 50 years	0.56	0.94
Females older than 50, mobility impaired (1)	0.43	0.71
Females older than 50, mobility impaired (2)	0.37	0.61
Males younger than 30 years	1.11	1.85
Males 30-50 years old	0.97	1.62
Males older than 50 years	0.84	1.4
Males older than 50, mobility impaired (1)	0.64	1.06
Males older than 50, mobility impaired (2)	0.55	0.91
Population groups – crew	**Walking speed on flat terrain (e.g. corridors)**	
	Minimum (m/s)	**Maximum (m/s)**
Crew females	0.93	1.55
Crew males	1.11	1.85

Table 3.3: Walking speed on flat terrain *(MSC.1/Circ.1533)*

Population groups – passengers	Walking speed on stairs (m/s)			
	Stairs down		Stairs up	
	Min.	Max.	Min.	Max.
Females younger than 30 years	0.56	0.94	0.47	0.79
Females 30-50 years old	0.49	0.81	0.44	0.74
Females older than 50 years	0.45	0.75	0.37	0.61
Females older than 50, mobility impaired (1)	0.34	0.56	0.28	0.46
Females older than 50, mobility impaired (2)	0.29	0.49	0.23	0.39
Males younger than 30 years	0.76	1.26	0.5	0.84
Males 30-50 years old	0.64	1.07	0.47	0.79
Males older than 50 years	0.5	0.84	0.38	0.64
Males older than 50, mobility impaired (1)	0.38	0.64	0.29	0.49
Males older than 50, mobility impaired (2)	0.33	0.55	0.25	0.41
Population groups – Crew	**Walking speed on stairs (m/s)**			
	Stairs down		**Stairs up**	
	Min.	**Max.**	**Min.**	**Max.**
Crew females	0.56	0.94	0.47	0.79
Crew males	0.76	1.26	0.5	0.84

Table 3.4: Walking speed on stairs (MSC.1/Circ.1533)

Travel duration (T)

For the calculation of the travel duration (T), at least 500 simulation iterations should be performed for each of the 4 scenarios. These simulations should consist of at least 100 different populations created, i.e. 5 simulations with the same characteristics. If there are no significant differences in the results between those 5 simulations with the same parameters, all 500 simulations with different initial parameters will be performed, as proposed in MSC.1/Circ.1533.

The highest travel duration in ideal condition time (t_I) for each of the base scenarios is considered to be the 95% of the highest times calculated in total simulations of each given scenario. Those four t_I times are then compared and the highest among them is chosen as the travel duration (T).

3.2.5 LSA Code

International Life-Saving Appliance (LSA) Code was adopted by MSC at its 66th session (June 1996) by resolution MSC.48(66). It provides international requirements for the life-saving appliances required by chapter III of the 1974 SOLAS Convention. The Code was made mandatory by resolution MSC.47(66), whereby regulation III/34 determines that all life-saving appliances and arrangements shall comply with its requirements. It entered into force on 1 July 1998 and has been amended in accordance with SOLAS Article VIII. Each type of ship must have all the life-saving appliances specified by the IMO in order to ensure an increased level of safety in case of an accident. Below will be analyzed the individual and collective life-saving appliances available for every type of ship and play a key role in life saving in an emergency situation (LSA, 2013).

4 Features of Simulation of Evacuation Using Pathfinder Code

Modeling an evacuation, where its analysis is particularly complex, it is necessary to use computational simulation tools. Such softwares are based on a set of mathematical formulas and are essentially programs that allow the individual researcher to observe the specific phenomenon without performing it in reality. These softwares cover a wide range of analysis of various phenomena, since theoretically any phenomenon that can be expressed through equations and mathematical data can be simulated.

The software used for the simulations of the current thesis was Pathfinder, developed by Thunderhead Engineering (Pathfinder User Manual, 2019). This program for simulation needs has been also used for other studies (Papadakis, 2020), (Koromila et al., 2020).

4.1 Pathfinder

Pathfinder is an emergency and human output simulator and is a useful tool for modeling procedures such us ship evacuations. It Includes:

- graphical environment used by the user
- simulator
- 3D Results Viewer

One of the key features of this software is that it allows the evaluation of evacuation models giving realistic results in a fast way compared to other simulators offering a flexible way to control occupants and their behavior. Pathfinder uses a 3D triangle to represent the geometry of the model. As a result, Pathfinder can accurately visualize geometric details and curves, while continuous movement of occupants is enabled throughout the model.

4.2 Simulation Parameters

The basic characteristics of the persons involved in evacuation can be divided into two major categories, their profile and their behavior during evacuation. In the profile, features of the person are included such as sex, age, body structure and their movement speed while in the behavior all those characteristics that will dictate his role and purpose in carrying out the evacuation. This separation is made primarily for the convenience of introducing these features into the program and performing the simulation.

4.2.1 Occupants Profiles

Pathfinder includes a pre-installed library of occupants’ profiles “imo_speed_profiles.plib” based on the IMO's Revised Guidelines for Passenger Ships (MSC.1/Circ.1533) as referred in Table 3.1. Individuals are divided according to certain categories and take different characteristics according to the category they belong, as mentioned in chapter 3.2.4: Advanced method of IMO. For simplicity reasons, the basic category profile of our simulations for 100% of occupants was chosen as “Males 30-50 years old”.

4.2.2 Body Structures

The body structure of each individual (shoulder width) is determined by the diameter of the cylinder that the individual represents and is useful in congestion situations and route selection during simulation. This value will affect how many people can be added to a room without overlaps and also the flow of occupants from doors. The body diameter was modified for each category above, using a uniform distribution. This provides a more realistic depiction of occupants within the space. For males 30-50 years old is between 40 and 44.2cm. In addition, a reduction factor is used, the coefficient that reduces the radius of the person, equal to 0.7.

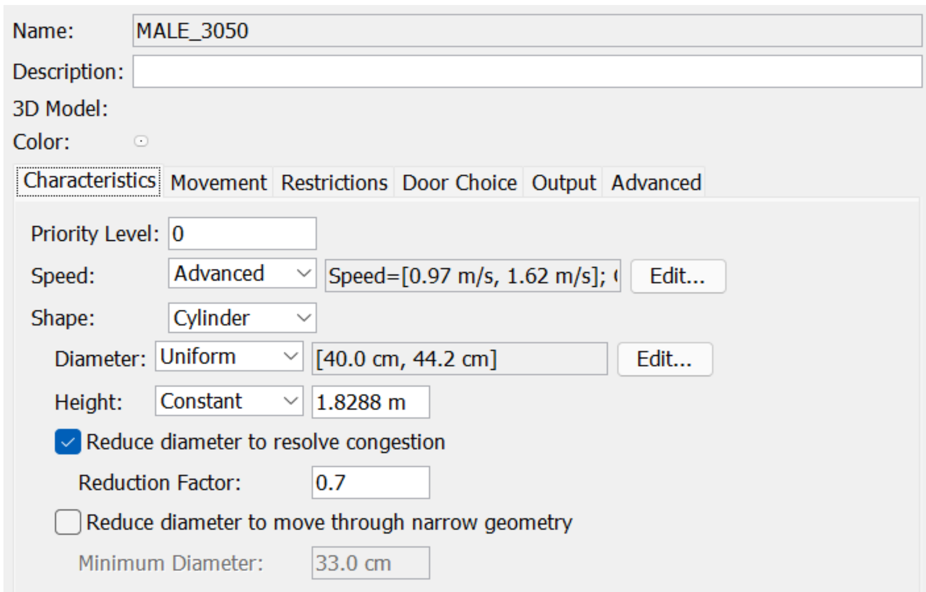


Figure 4.1: Diameter modification & reduction factor

4.2.3 Movement Speed

The speed of individuals varies according to the population composition categories described in Tables 3.2 and 3.3, with minimum and maximum values of the walking speeds to be modeled as a uniform distribution, both for flat terrain and stairs.

For the males 30-50 years old, flat terrain walking speed has a minimum of 0.97 m/s and a maximum of 1.62 m/s, whereas the stars-down minimum and maximum speeds are 0.64 m/s and 1.07 m/s, respectively. Stairs-up values are 0.47 m/s and 0.79 m/s, too. It is worth noting that distributions according to IMO were applied only for flat terrain. For the stairway speeds, the average values were chosen, due to unavailability to use distributions in the program.

4.2.4 Behavior

An important parameter in the study of evacuation is the behavior of each occupant separately from the rest population. Each occupant is defined by a behavior. Its behavior is what determines its scopes in this process, i.e. defining a series of actions that the passenger will perform throughout the simulation. This allows for example a passenger to wait in a particular room for a predetermined time (initial delay) and then go to exits.

4.2.5 Initial Delay

The initial delay is a key part of the behavior and is the time between the start of the evacuation, the moment when we assume the sound of the siren to inform the passengers and the crew that there is an emergency until the start of each passenger. It coincides with the response time as described in chapter 3.2.4 "Response duration". This time can be a crucial factor for a successful ship evacuation.

4.2.6 Basic Motion Modes

Pathfinder supports two basic ways to simulate motion:

1. Steering mode
2. SFPE mode

In the Steering function, passengers are moved by a steering system which defines the occupants to move independently in the area. Essentially, this function enables occupants try to mimic human motion and behavior as much as possible.

Instead, SFPE uses a set of assumptions for the behavior of individuals, derived from the Engineering Guide to Human Behavior in Fire (SFPE, 2003). The speed of occupants is determined by the door flow rate. Yet individuals do not avoid each other, but they are allowed to penetrate each other.

In addition, there is a third mode,

3. SFPE+Steering

Choosing the Steering mode but in the Behavior Mode tab, enabling the Limit Door Flow Rate option, in which the flow of persons at the exits is controlled in advance by setting the maximum value of the specific flow rate (persons/m/s), the combined version is activated. More explanatory differences between those three modes are given in chapter 5: IMO TESTS.

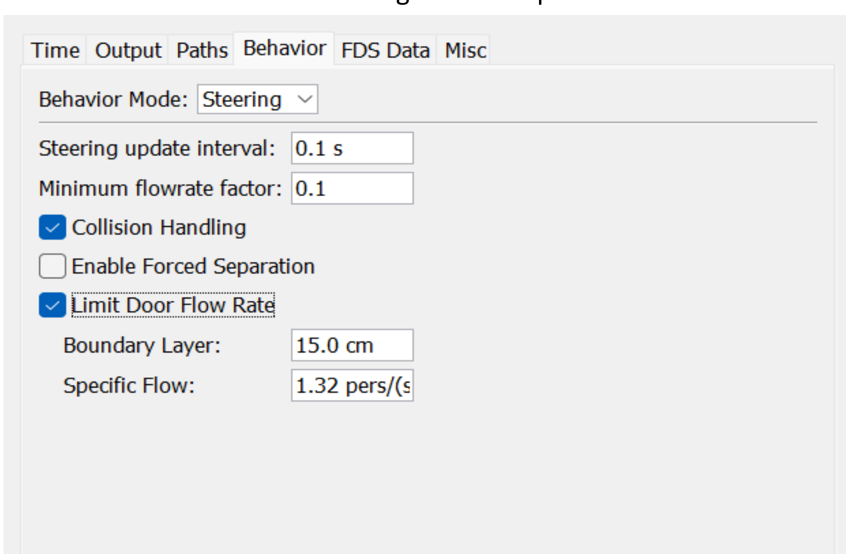


Figure 4.2: SFPE + Steering mode settings

More explanatory differences between those three modes are given in chapter 5: IMO TESTS.

4.3 Congestion

A phenomenon that plays a crucial in evacuation time, on pathfinder simulations is congestion. It is defined as excessive concentration of occupants in a specific area and is identified by one of the following criteria (IMO, 2016)

- density (D) equal to, or greater than 3.5 persons/m^2
- flow rate (Fs) equal to, or greater than 1.5 persons/sec

Data to measure this occupant count over time is available in the *doors.csv* output file and is processed using a spreadsheet. In some cases, those congestion levels may not be significant for the evacuation process, but if they keep at such high values for more than 10% of the total $t_{assembly}$, these areas are considered critical.

5 IMO Tests

Thunderhead Engineering in the verification & validation document presentation, having carried out a series of verification and validation data tests for the Pathfinder simulator (Thunderhead Engineering ,2015). Before starting, a few definitions are used throughout this document:

- Verification tests: synthetic test cases designed to ensure that the simulator is performing as specified by the Pathfinder Technical Reference. Usually these tests attempt to isolate specific simulated quantities or behaviors and may include only a small number of occupants. This type of test often has very specific pass/fail criteria. Verification tests ensure that the software implements a particular model correctly – they are not designed to measure how accurately that model reflects reality.
- Validation tests: are designed to measure how well Pathfinder's implementation of simulation models captures real behavior. Usually these tests will explore the interaction between multiple simulation elements and may have less specific pass/fail criteria. Validation tests are usually based on experimental data or experience (e.g. congestion should form at a particular location).
- Comparisons: present Pathfinder results alongside the results of other simulators. These tests are designed to give the reader a sense of where Pathfinder "fits in" relative to other simulation software.

5.1 Simulation Modes

Test cases were executed by the use of the three aforementioned modes based on the behavior mode option and the limit door flow rate option in Pathfinder's simulation parameters dialog.

- SFPE
- Steering
- SFPE + Steering

In each case, all other simulator options are left at the default setting unless otherwise specified. For cases that examine speed-density behavior, only the Steering mode is applicable.

Annex 3 of MSC.1/Circ.1238 (IMO, 2007) presents a guidance on validation and verification of evacuation simulation tools in order to respond as intended. Eleven (11) tests in total are presented. Thus, it is crucial to carry out these tests in the pathfinder simulator to ensure the validity and verification of it towards the upcoming evacuation simulations and their results. The tests presented are:

- IMO 1: Movement Speed
- IMO 2: Stairway Speed, Up
- IMO 3: Stairway Speed, Down
- IMO 4: Door Flow Rates
- IMO 5: Initial Delay Time
- IMO 6: Rounding Corners

- IMO 7: Multiple Movement Speeds
- IMO 8: Counter-flow
- IMO 9: Sensitivity to Available Doors
- IMO 10: Exit Assignments
- IMO 11: Congestion

IMO Tests 1,2 and 3 will not be analyzed, as they are included in the other tests as basic ones.

5.2 Door Flow Rates (IMO_04)

Description:

The 4th test confirms Pathfinder's flow rate limits imposed by doorways in the SFPE modes. Steering mode results are also compared. It is based on Test 4 given in MSC.1/Circ.1533 /Annex 3. There is one 8X5-meter room, with a 1-meter door in the center of the 5-meter wall. 100 occupants are distributed on the one room, expecting the flow rate to be no more than 1.33 persons/sec for the total duration of exiting. Figure 5.1 shows the problem setup of simulation test 4.

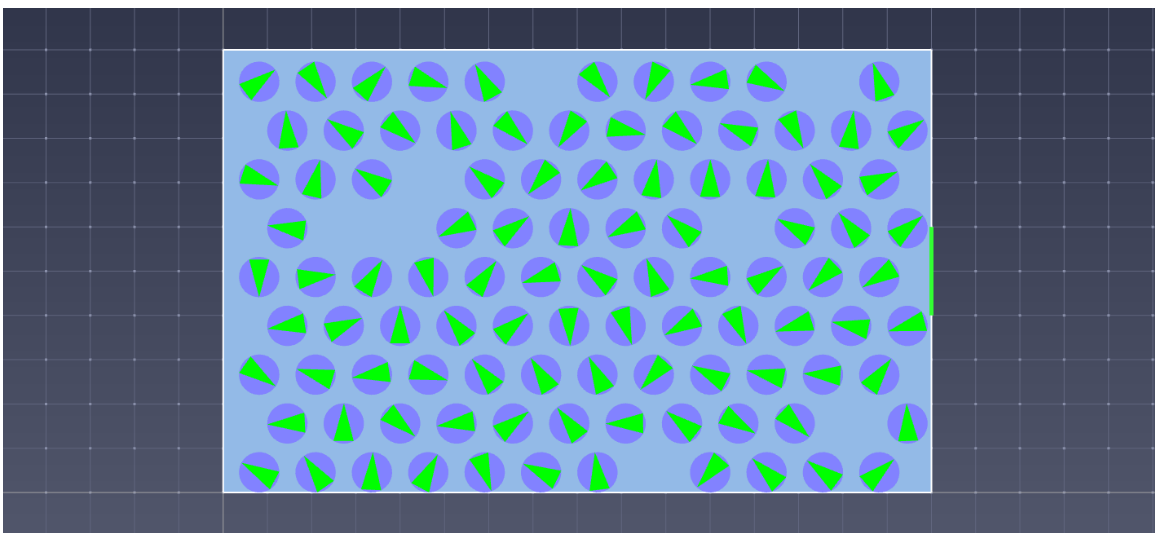


Figure 5.1: IMO_4 problem setup

Setup notes:

Average flow rate is defined as the number of occupants to pass through a door divided by the amount of time the door was "active." A door is considered to be active from the exiting time of the first and until the exiting of the last occupant.

According to the SFPE guidelines, the boundary layer for the SFPE mode simulations is 0.15 m. There is no boundary layer in Steering mode (the entire 1-meter door width is always used). For the SFPE mode, the expected door flow rate is 0.92 pers/s when a 15 cm boundary is included.

Expected Results:

Maximum flow rate should be no more than 1.33 pers/s.

Simulation Results:

Table 5.1 shows the exit door average flow rate in the three modes (0 boundary in SFPE mode).

MODE	Average Flow Rate (pers/s)
SFPE	0.92
SFPE + Steering	0.86
Steering	1.3

Table 5.1: IMO 4 test results

Steering mode results to higher average flow rates through doors, due to the interaction of the occupants, whereas SFPE and SFPE + Steering control directly the flow rate based on the SFPE specifications, thus their results are close.

5.3 Initial Delay Time (IMO_05)

Description:

The 5th test confirms Pathfinder's initial delay (pre-movement) times. It is based on Test 5 given in MSC.1/Circ.1533 /Annex 3. There is one 8X5-meter room, with a 1-meter door in the center of the 5-meter wall. 10 occupants in it, with the response times as a uniform distribution between 10 and 100 seconds. Figure 5.2 shows the problem setup of simulation test 5:

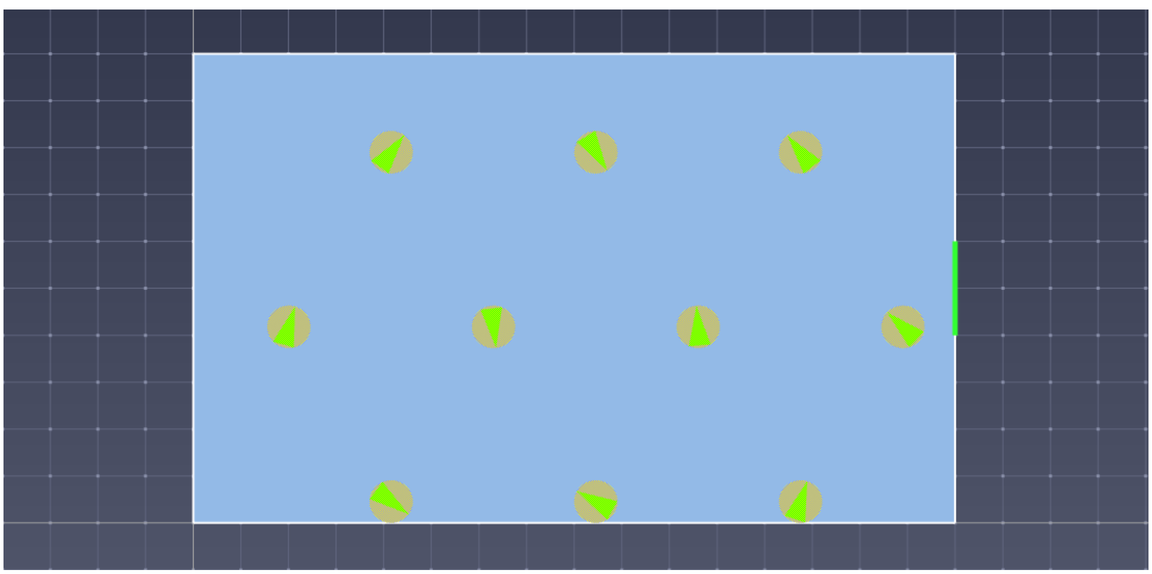


Figure 5.2: IMO_5 problem setup

Setup notes:

Occupants are assigned initial delays varying between 10 and 100 s.

Expected Results:

Maximum flow rate should be no more than 1.33 pers/s.

Simulation Results:

Response time differences can be verified by both the results animation and the occupants detailed .CSV output files. Figure 5.3 shows a frame that three occupants still have an initial delay and one occupant is moving towards the exit door.

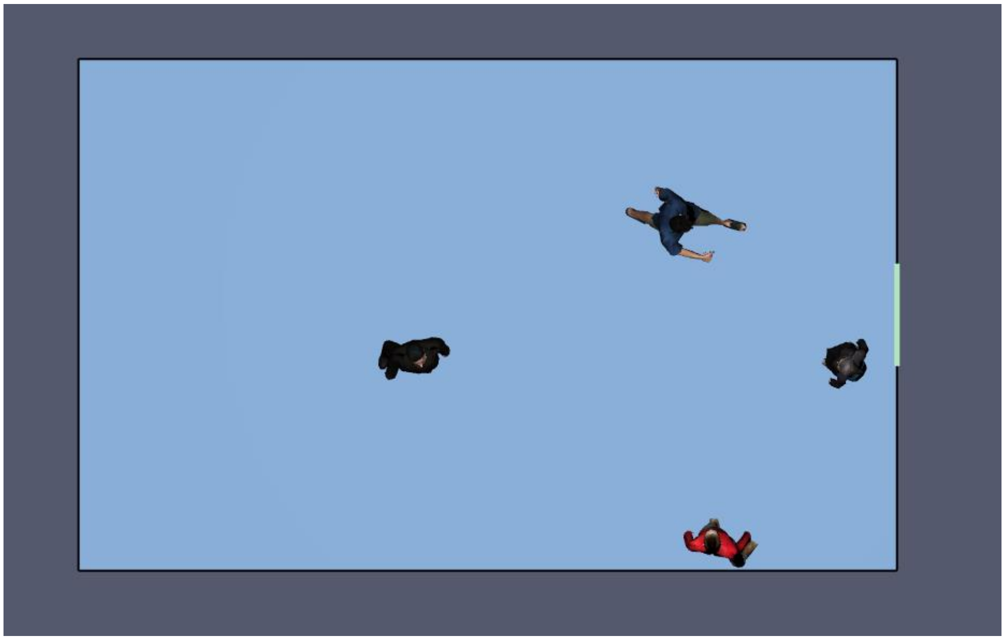


Figure 5.3: Screenshot of the simulation showing the response of 1 occupant and the initial delay of 3 others

Figure 5.4 shows the detailed output data for occupant "4", who had an initial delay time of 83 seconds. The movement begins after 83 seconds and the occupant exits the room at 85 s.

t	id	name	active	x	y	z	v	distance	location	terrain typ
s				m	m	m	m/s	m		
69	3	4	0	6.37704	0.227901	0	0	0	Room00	level
70	3	4	0	6.37704	0.227901	0	0	0	Room00	level
71	3	4	0	6.37704	0.227901	0	0	0	Room00	level
72	3	4	0	6.37704	0.227901	0	0	0	Room00	level
73	3	4	0	6.37704	0.227901	0	0	0	Room00	level
74	3	4	0	6.37704	0.227901	0	0	0	Room00	level
75	3	4	0	6.37704	0.227901	0	0	0	Room00	level
76	3	4	0	6.37704	0.227901	0	0	0	Room00	level
77	3	4	0	6.37704	0.227901	0	0	0	Room00	level
78	3	4	0	6.37704	0.227901	0	0	0	Room00	level
79	3	4	0	6.37704	0.227901	0	0	0	Room00	level
80	3	4	0	6.37704	0.227901	0	0	0	Room00	level
81	3	4	0	6.37704	0.227901	0	0	0	Room00	level
82	3	4	0	6.37704	0.227901	0	0	0	Room00	level
83	3	4	0	6.37704	0.227901	0	0	0	Room00	level
84	3	4	1	6.93557	0.961787	0	1.19	0.92225	Room00	level
85	3	4	1	7.656254	1.908738	0	1.19	2.11225	Room00	level
86	3	4	0	8	2.227957	0	0.201958	2.607304		level

Figure 5.4: Output file for occupant 4. This occupant had a delay time of 83 s, so movement is recorded from 84 s until 85 s that exits

All of the three modes passed the test.

5.4 **Rounding Corners (IMO_06)**

Description:

The 6th test confirms the ability of occupants to round in corners in Pathfinder. It is based on Test 6 given in MSC.1/Circ.1533 /Annex 3. 20 occupants round on a corner of a wide corridor. The expectation is not to penetrate any model geometry but round on the corner of the model. Figure 5.5 shows the problem setup of simulation test 6:

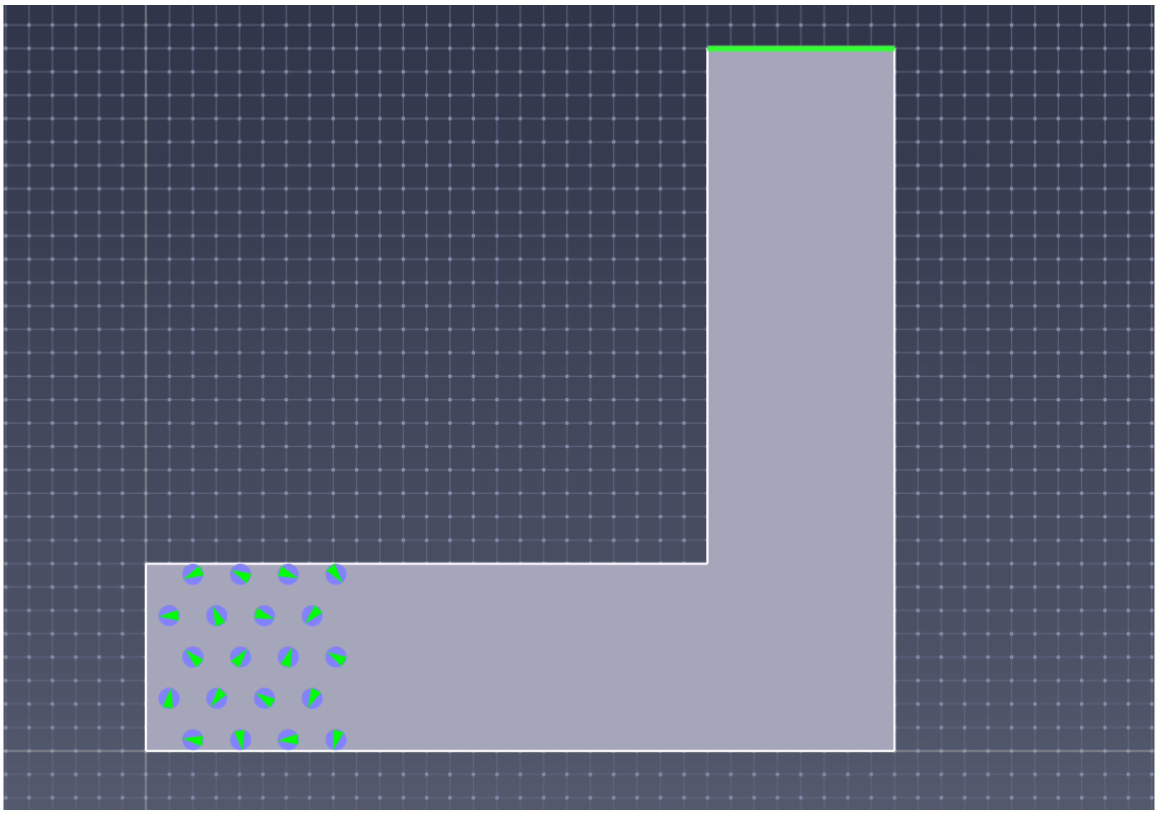


Figure 5.5: IMO_6 problem setup

Setup notes:

20 persons are uniformly distributed in the first 5 meters of the corridor.

Expected Results:

All of the occupants should stay within the boundaries of the model geometry and round the corner. On SFPE mode ocuupants can pass through each other, whereas in SFPE and SFPE + Steering they keep their distances to each other.

Simulation Results:

All three modes successfully had the corner rounding done by the occupants and stayed within the geometry boundaries, presenting also their paths, as shown in Figure 5.6. Additionally, realistic representation of the occupants rounding the corner is also shown in Figure 5.7.

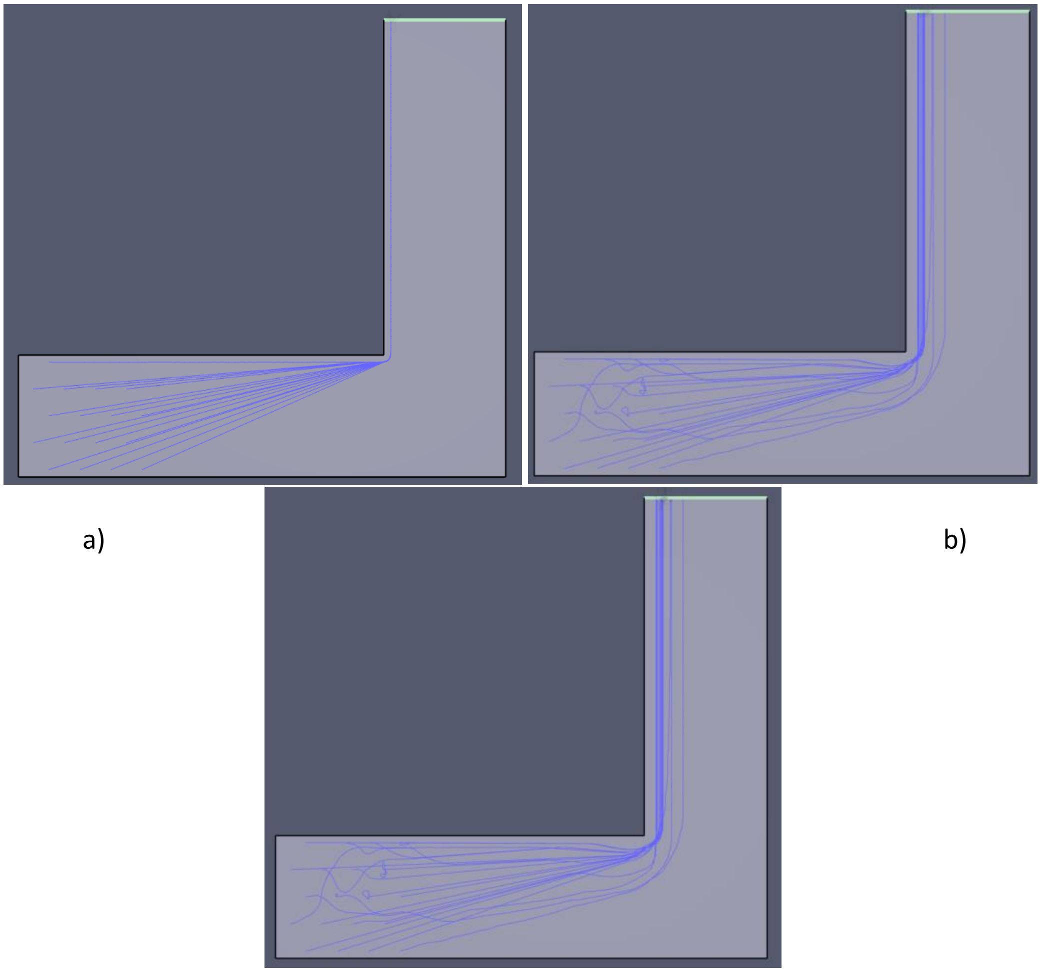


Figure 5.6: Occupant trails for boundary test: (a) SFPE (b) Steering + SFPE (c) Steering mode

Figure 5.7: Realistic view of occupants rounding the corner (Steering mode)

Regarding the simulations, SFPE mode is not as realistic as the other 2 modes in this model.

5.5 Multiple Movement Speeds (IMO_07)

Description:

The 7th test confirms the existence of multiple walking speeds in Pathfinder. It is based on Test 7 given in MSC.1/Circ.1533 /Annex 3. The model includes 40.5X51-meter room with a door across the entire right side of the room. 50 occupants, lined 0.5 m from the left side, are assigned different movement speeds and must walk in a straight line each, to exit. Figure 5.8 shows the problem setup of simulation test 7:

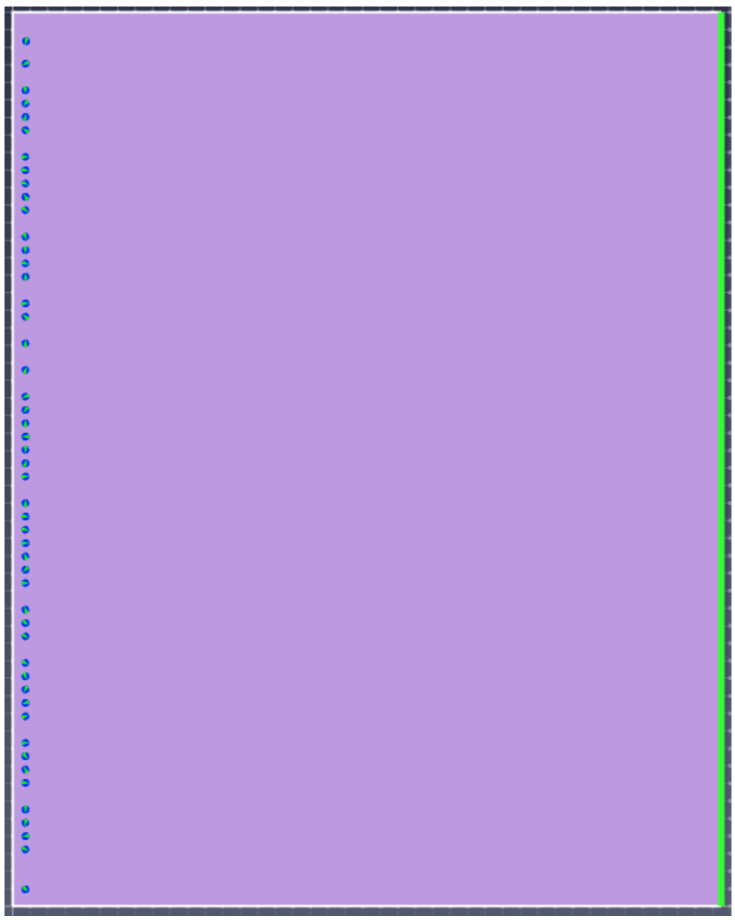


Figure 5.8: IMO_7 problem setup

Setup notes:

The occupants' profile is one of the IMO proposed ones, as occurred by MSC.1/Circ.1533/Annex 2. The profile is formed by males 30-50 years old, with walking speeds of uniform random distribution and a range of [0.97 m/s, 1.62 m/s].

Expected Results:

The arrival times of occupants, at the right side of the room, should vary, depending on their different walking speed they have, within the specified limits. This time should be between 24.7s and 41.2 s (without also considering inertia in Steering mode) for all of the modes.

Simulation Results:

The walking speeds of occupants are indeed within the acceptable range. The times of first and last arrivals are presented for each mode in Table 5.2, and the trails of occupants during their exit way are shown in Figure 5.9.

MODE	First Arrival (s)	Last Arrival (s)
SFPE	25.7	42
SFPE + Steering	26.3	43
Steering	26.3	43

Table 5.2: IMO 7 test results

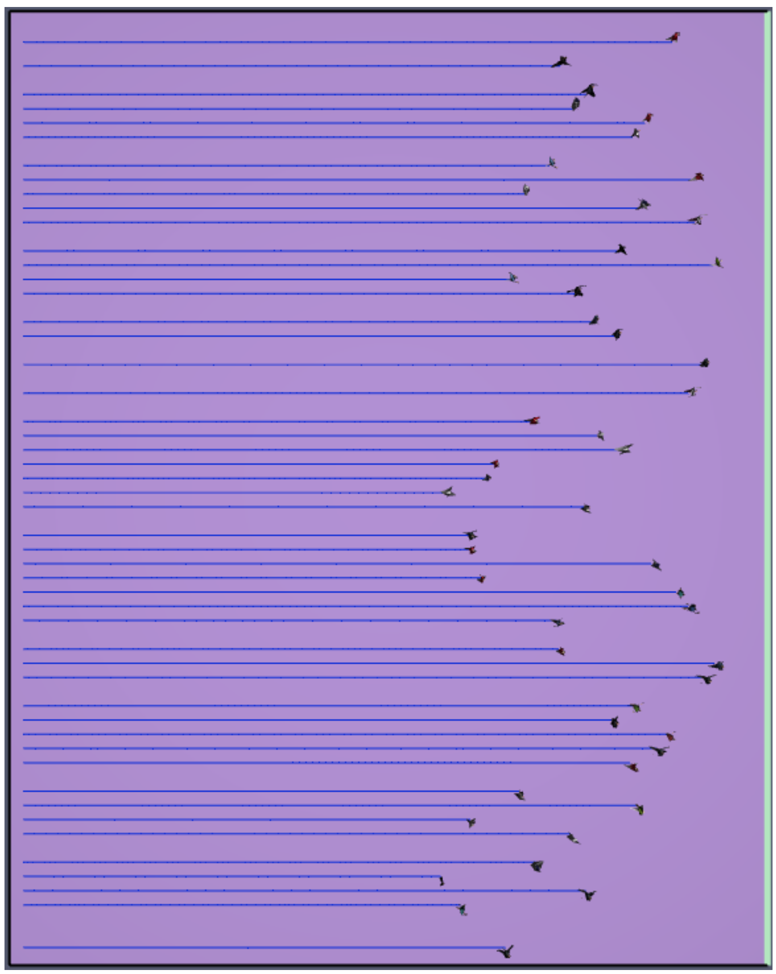


Figure 5.9: MO_07 results showing occupants paths at 24 s

All of the three modes passed the test.

5.6 Counterflow (IMO_08)

Description:

The 8th test confirms Pathfinder's effectiveness on counter-flow. It is based on Test 8 given in MSC.1/Circ.1533 /Annex 3. Two 10X10-meter rooms, are linked via a 10X2-meter corridor. 100 occupants are distributed on the one room, and move through the corridor to the other one. The test is run with 100 and 200 occupants (100 in the left room, walking on the opposite direction, in counter-flow to the original group.

Setup notes:

The occupants' profile is one of the IMO proposed ones, as occurred by MSC.1/Circ.1533/Annex 2. The profile is formed by males 30-50 years old, with walking speeds of uniform random distribution and a range of [0.97 m/s, 1.62 m/s].

Expected Results:

Increase of occupants in counter-flow leads to increased simulation time. Figure 5.10 shows the problem setup of simulation test 8.

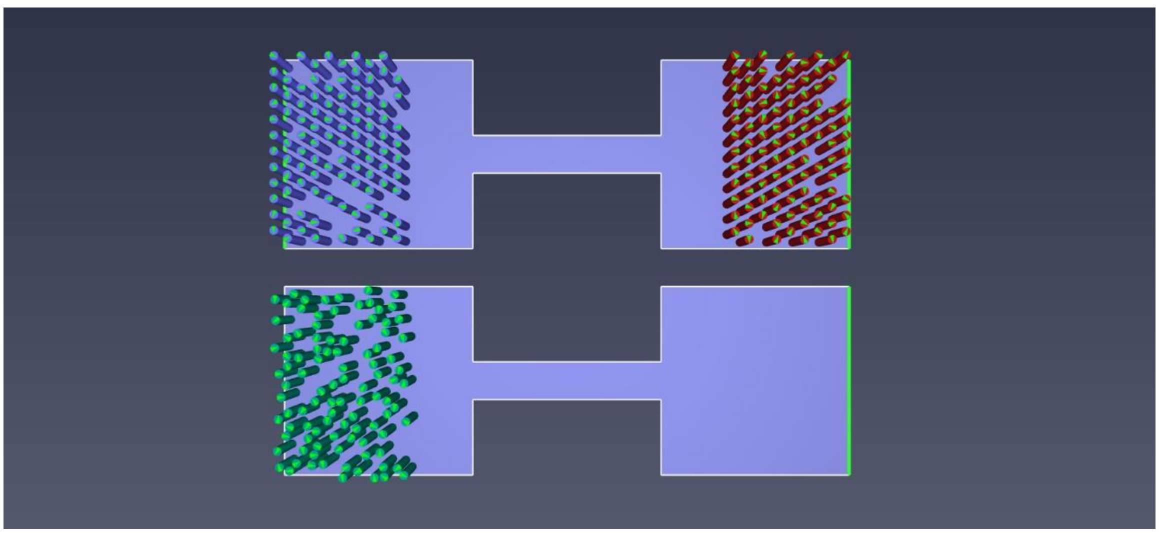


Figure 5.10: IMO_8 problem setup

Simulation Results:

Table 5.3 shows the necessary time of the original group to exit the simulation with each of 3 modes. 'First exiting' indicates the first occupant's exiting time and 'Last exiting' shows the last occupant's exiting time, in both 100 and 200 occupants' cases.

	MODE	100 occupants		200 occupants	
IMO 8		First exiting (s)	Last exiting (s)	First exiting (s)	Last exiting (s)
	Steering	16.9	63.8	23.8	254.6
	Steering+SFPE	16.9	63.8	23.8	254.6
	SFPE	15.1	30.9	16.9	32.2

Table 5.3: IMO 8 test results

Figure 5.11 and 5.12 shows the Cumulative number of exited occupants in SFPE and Steering mode. In this test SFPE+Steering mode has identical exit times with Steering mode.

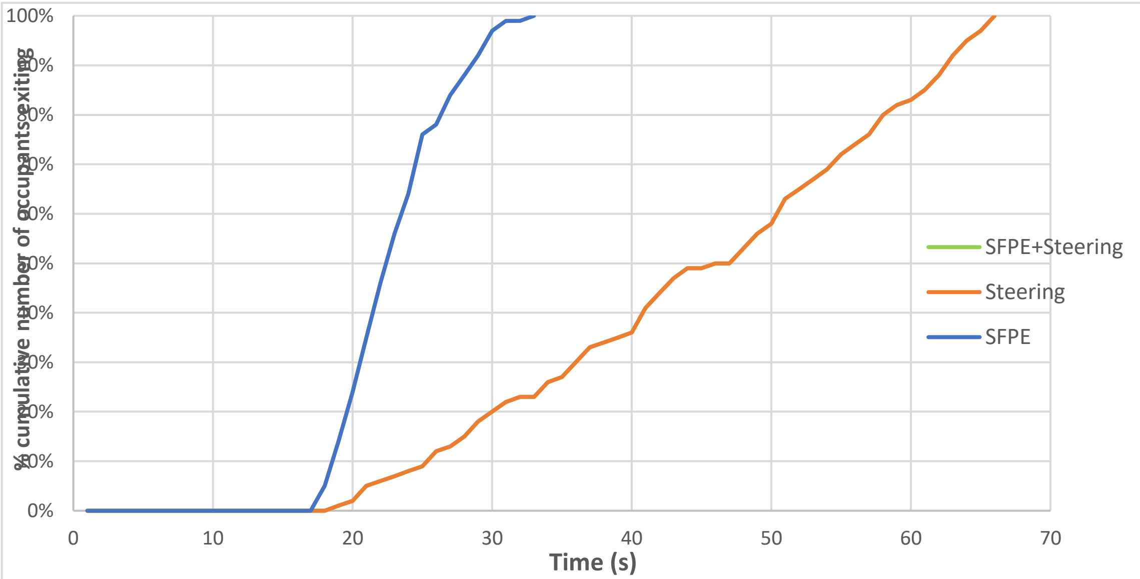


Figure 5.11: Cumulative number of 100 occupants exiting (SFPE, Steering & SFPE+Steering mode)

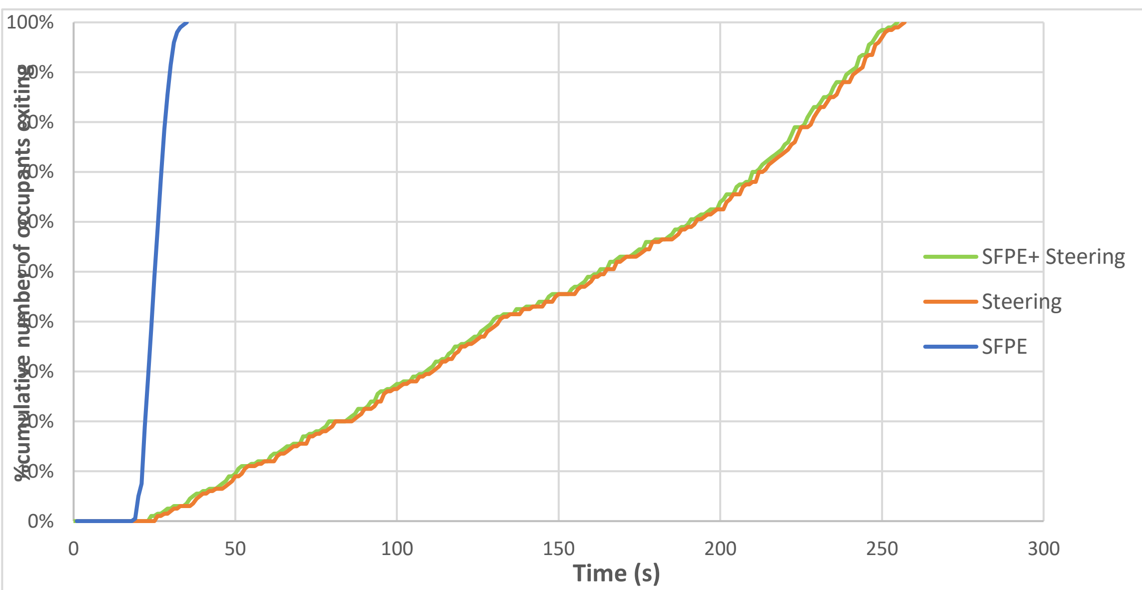


Figure 5.12: Cumulative number of 200 occupants exiting (SFPE, Steering & SFPE+Steering mode)

SFPE mode has no counterflow interference. As a result, in SFPE exit time is significantly lower than the other modes. Figures 5.13, 5.14 & 5.15 show occupants' positions during the simulations.

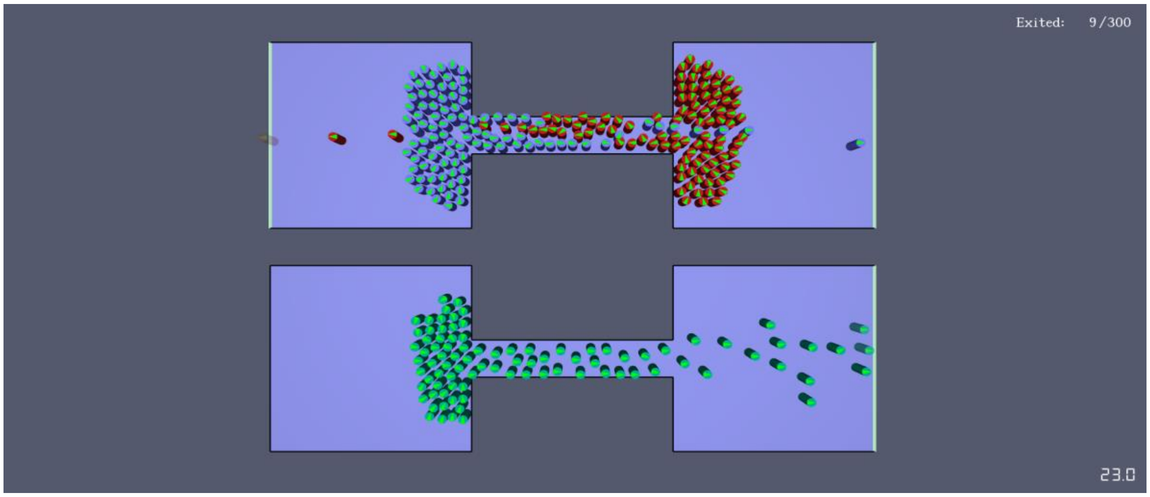


Figure 5.13: Occupant positions, 100-person counterflow case at 23 sec. (Steering mode)

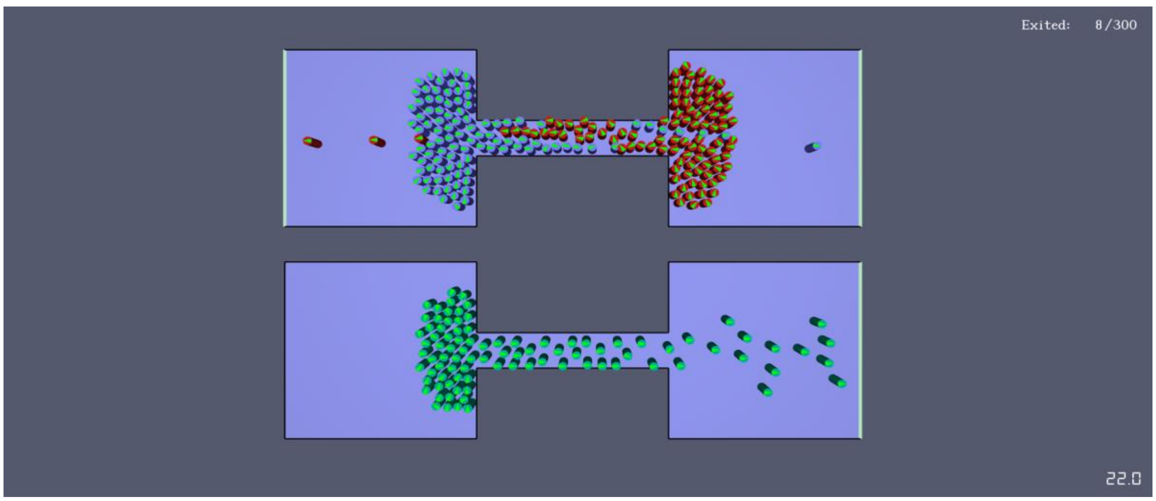


Figure 5.14: Occupant positions, 100-person counterflow case at 22 sec. (SFPE + Steering mode)

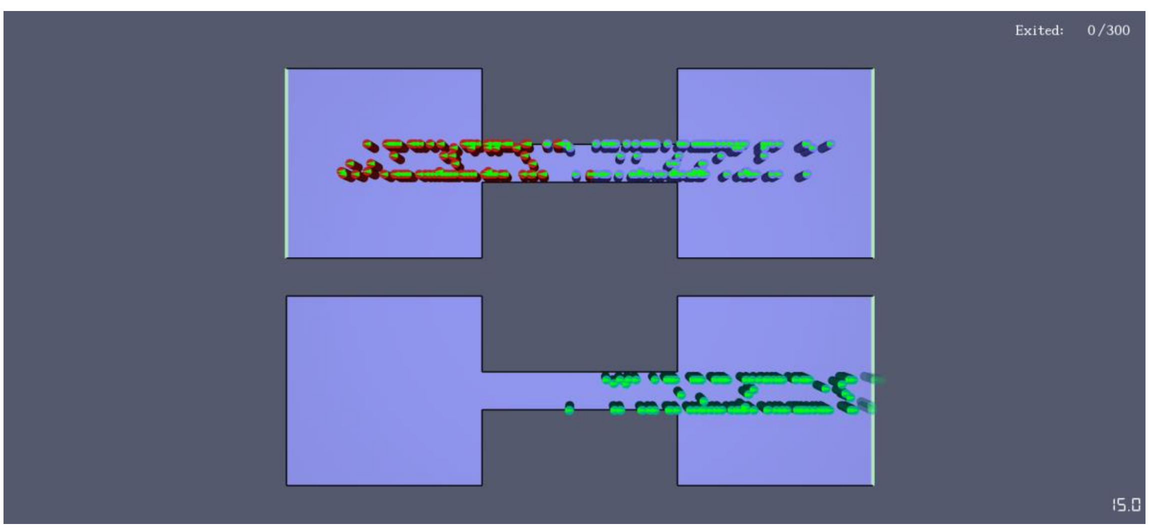


Figure 5.15: Occupant positions, 100-person counterflow case at 15 sec. (SFPE mode)

5.7 Sensitivity to Available Doors (IMO_09)

Description:

The 9th test confirms Pathfinder's exit time sensitivity to alternation of the number of available exit doors. It is based on Test 9 given in MSC.1/Circ.1533 /Annex 3. 1000 occupants are uniformly distributed centrally in a 30X20-meter room, 2 meters away from each wall, with exit doors of 1 m width. Two scenarios are tested; with 2 and 4 exits, expecting that the evacuation time will be half in the 4-exit case. Figure 5.16 shows the problem setup of simulation test 9.

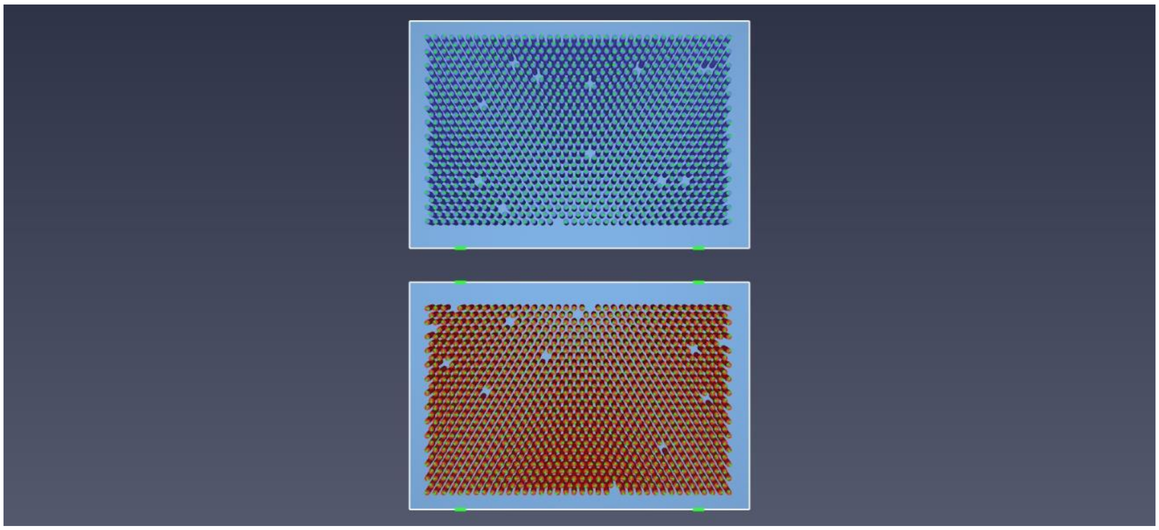


Figure 5.16: IMO_9 problem setup

Setup Notes:

The occupants' profile is one of the IMO proposed ones, as occurred by MSC.1/Circ.1533/Annex 2. The profile is formed by males 30-50 years old, with walking speeds of uniform random distribution and a range of [0.97 m/s, 1.62 m/s].

Expected Results:

Simulation time should approximately double when using half as many doors.

Simulation Results:

Table 5.4 shows the necessary time to exit the simulation for both scenarios. The 'min' indicates the door exiting time that passed the first occupant by, whereas the 'max' indicates the door exiting time that passed the last occupant by, for each scenario.

	MODE	4 doors		2 doors	
		Min (s)	Max (s)	Min (s)	Max (s)
IMO 9	Steering	218.2	220.2	424.3	434.5
	Steering+SFPE	292.7	305.8	607.6	609.9
	SFPE	266.3	280.3	539.2	554.2

Table 5.4: IMO 9 test results

For all modes, the simulation times, while not exactly double, are well within the acceptable margin for validity.

Figure 5.17 and 5.18 is shown the Cumulative number of exited occupants in SFPE, Steering and SFPE & Steering mode, in both 4 & 2 exit doors cases.

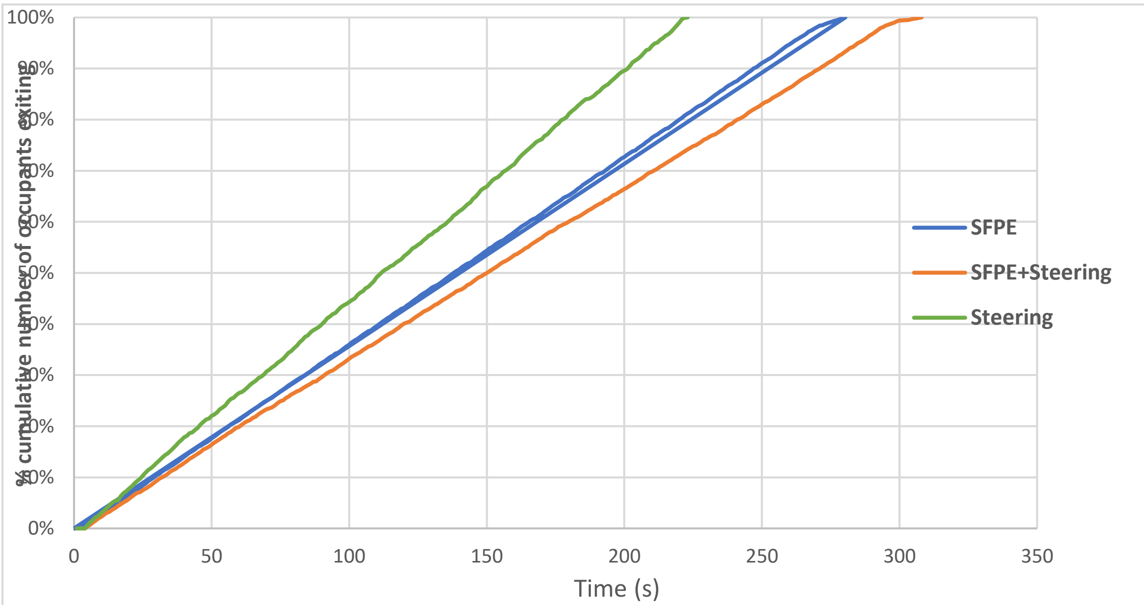


Figure 5.17: Cumulative number of exiting occupants 4-doors case, SFPE, SFPE + Steering, Steering mode

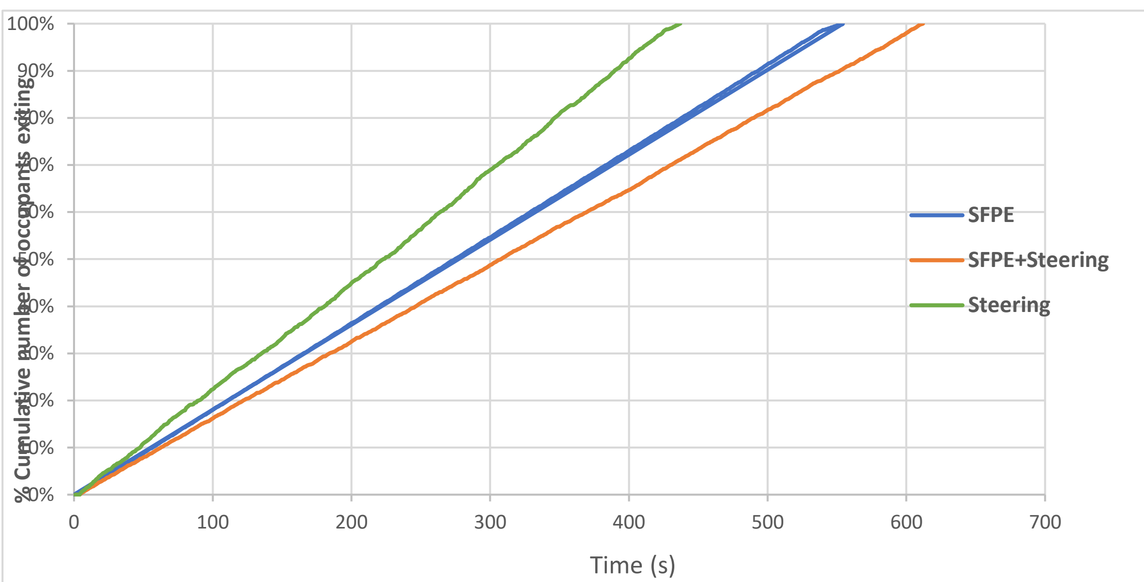
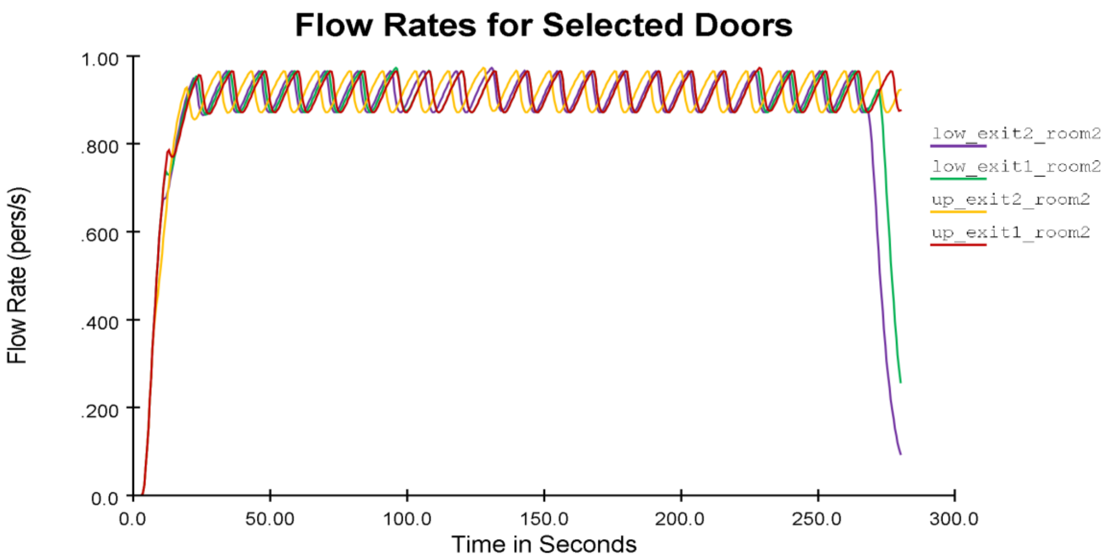
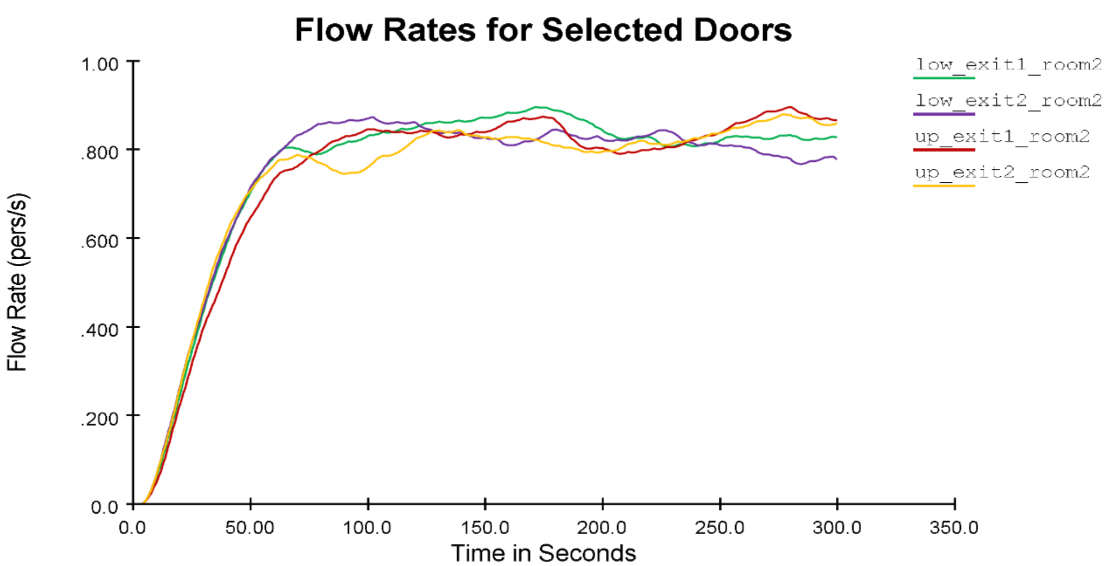


Figure 5.18: Cumulative number of occupants exiting 2-doors case, SFPE, SFPE + Steering, Steering mode

Figure 5.19 & 5.20 show the flow rates of the three modes in the 4-door and 2-door cases, respectively. SFPE mode's form of graphs are a repetitive pattern that keeps a steady rate of an average flow 0.9 pers/s. This low rate occurs because occupants can walk through each other, without interaction, so there is no queue to their exiting. The opposite happens on the steering mode, as there is interaction between occupants, resulting in higher flow rates over 1 pers/s. The SFPE + Steering mode keeps the lowest flow rates around 0.8 pers/s as it behaves as the steering mode, but keeping a limitation to the door flow rate resulting in low rate values. Occupants paths and exit queuing in SFPE, Steering and SFPE + Steering modes are shown in Figures 5.21, 5.22 & 5.23, respectively.





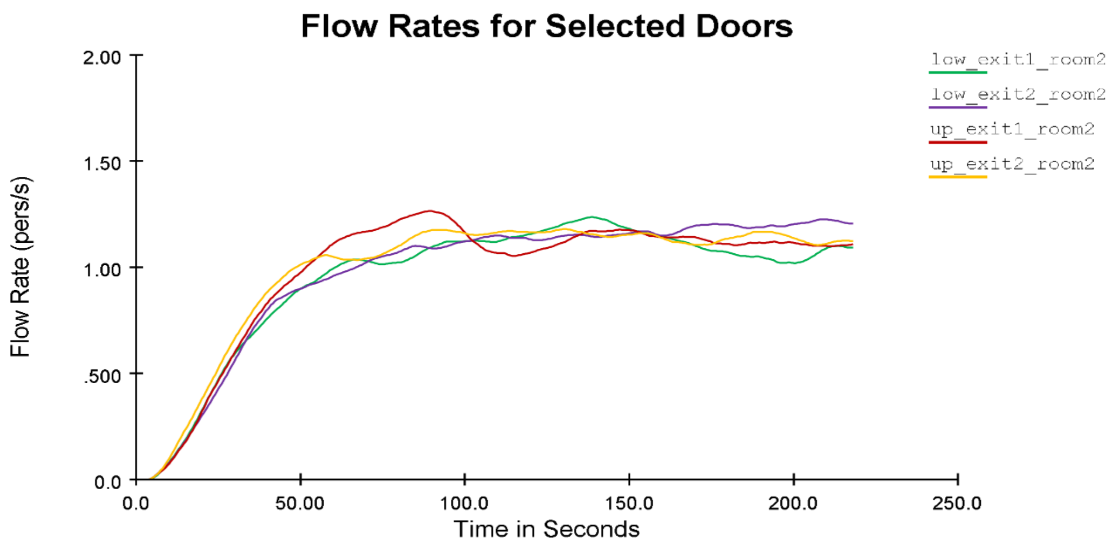
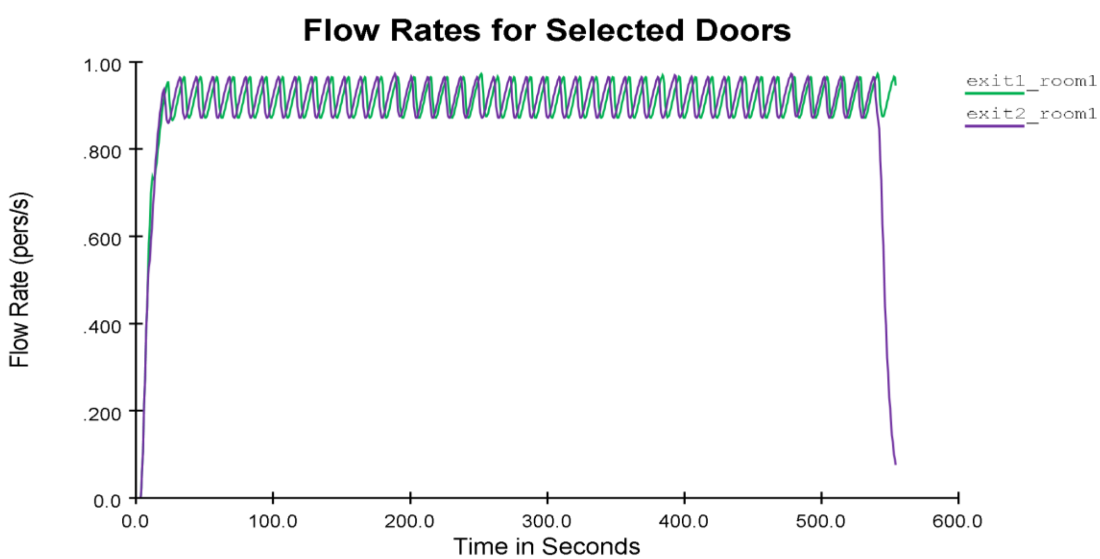
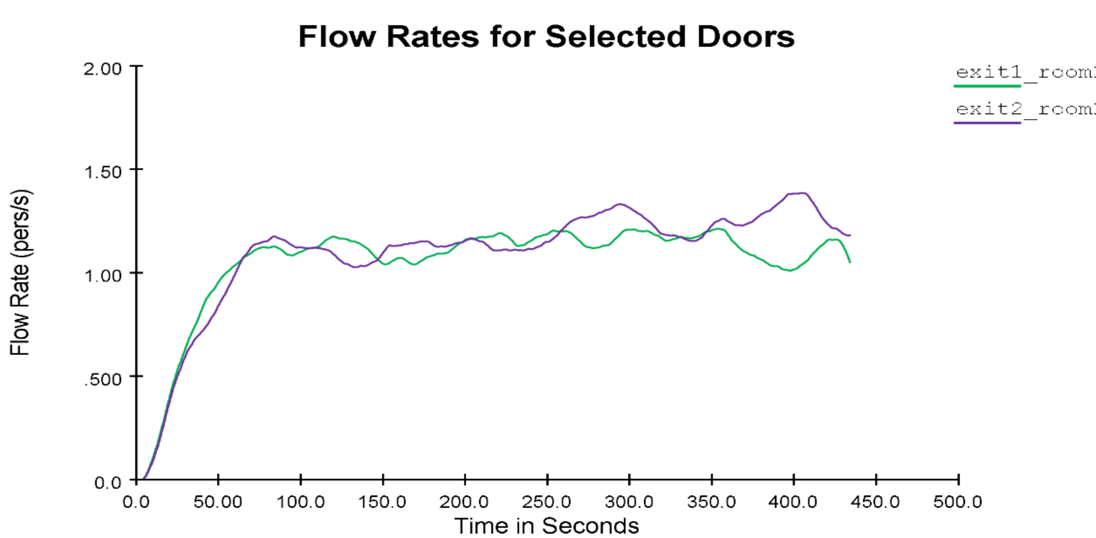


Figure 5.19: Exit flow rates for exit doors in 4-doors case i) SFPE ii) SFPE + Steering iii) Steering mode





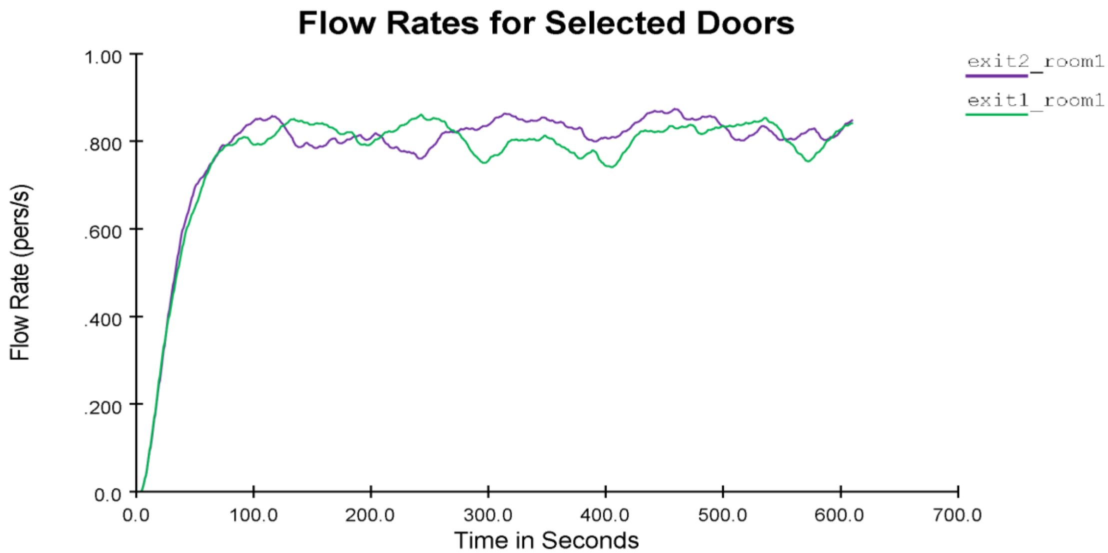


Figure 5.20: Exit flow rates for exit doors in 2-doors case i) SFPE ii) SFPE + Steering iii) Steering mode

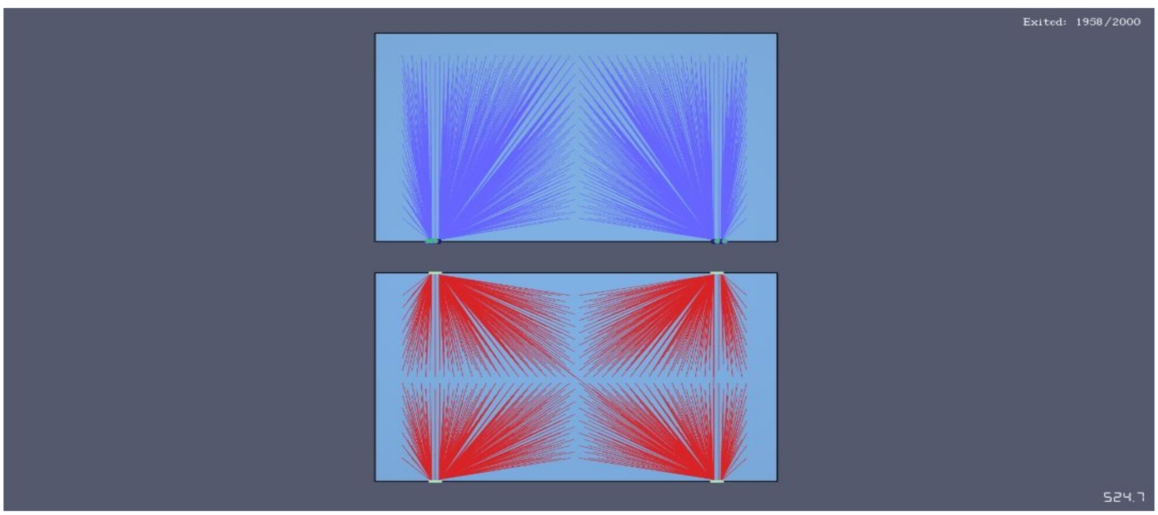


Figure 5.21: Occupants paths to exit doors (SFPE mode) up) 2 exits case low) 4 exits case

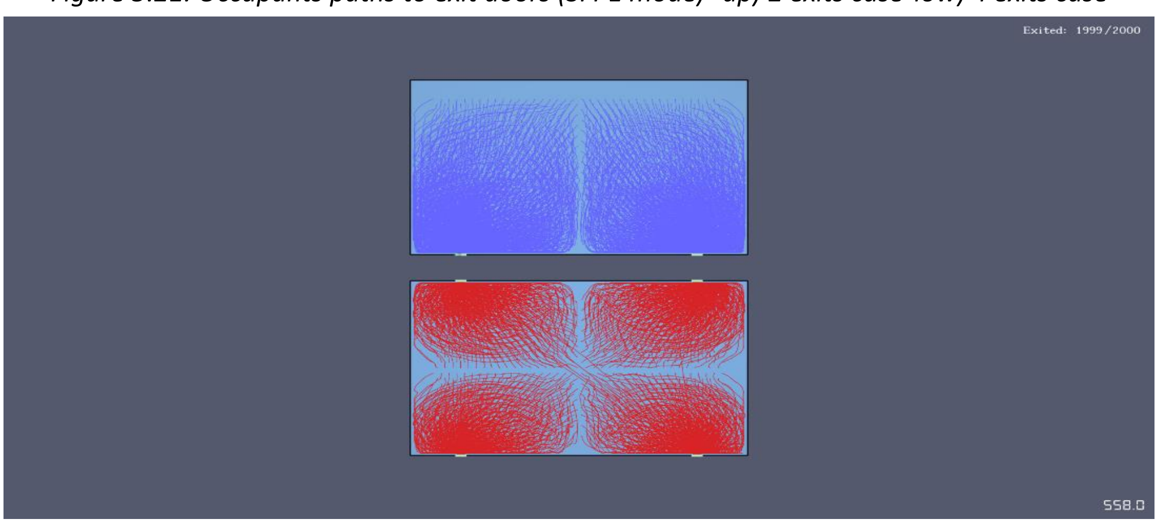


Figure 5.22: Occupants paths to exit doors (Steering mode) up) 2 exits case low) 4 exits case

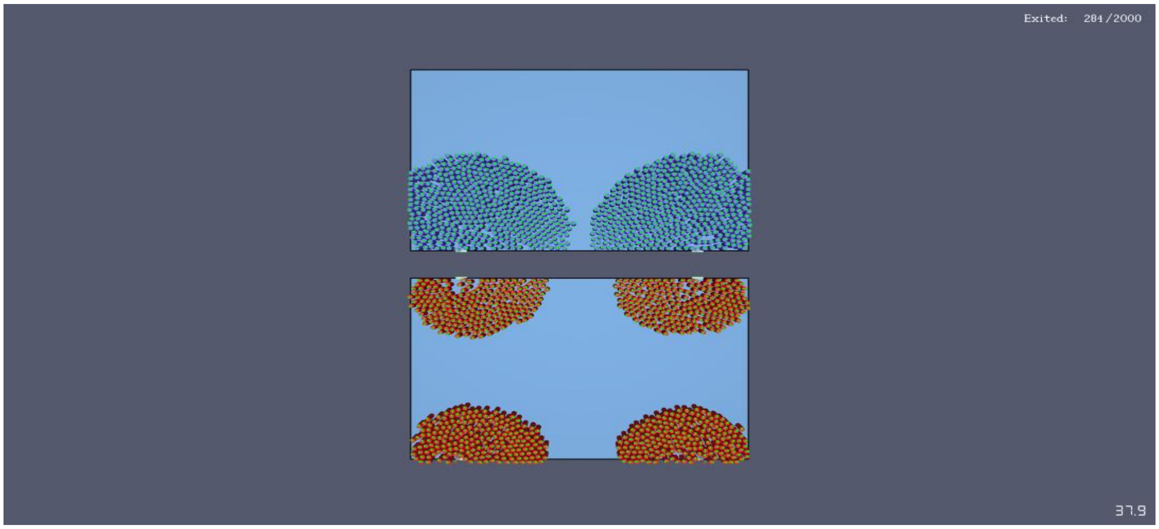


Figure 5.23: Occupants positions in 2 exits (up) and 4 exits (low) cases. (SFPE + Steering mode)

5.8 **Exit Assignments (IMO_10)**

Description:

The 10th test confirms exit assignments in Pathfinder. It is based on Test 10 given in MSC.1/Circ.1533 /Annex 3. 23 occupants are assigned to leave from a series of rooms that are placed, to specific exits. The model represents ship's cabins area. The 15 occupants in the left 8 rooms are assigned to the main (top) exit, while the 8 occupants in the remaining 4 rooms are assigned to the secondary (right) exit. Figure 5.24 shows the problem setup of simulation test 10.

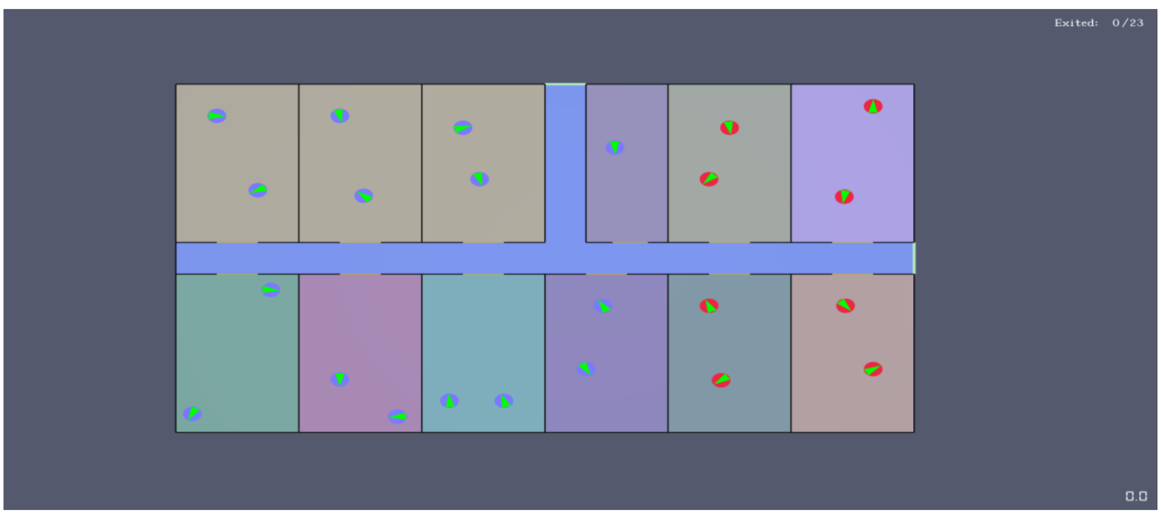


Figure 5.24: IMO_10 problem setup

Setup Notes:

The occupants' profile is one of the IMO proposed ones, as occurred by MSC.1/Circ.1533/Annex 2. The profile is formed by males 30-50 years old, with walking speeds of uniform random distribution and a range of [0.97 m/s, 1.62 m/s].

Expected Results:

All occupants should leave the model using their specified exit.

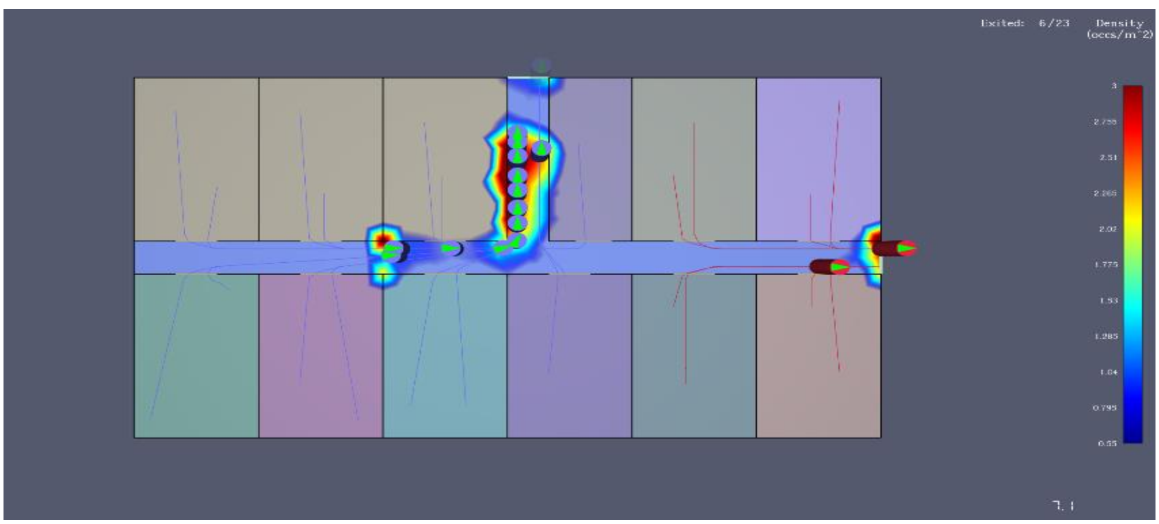
Simulation Results:

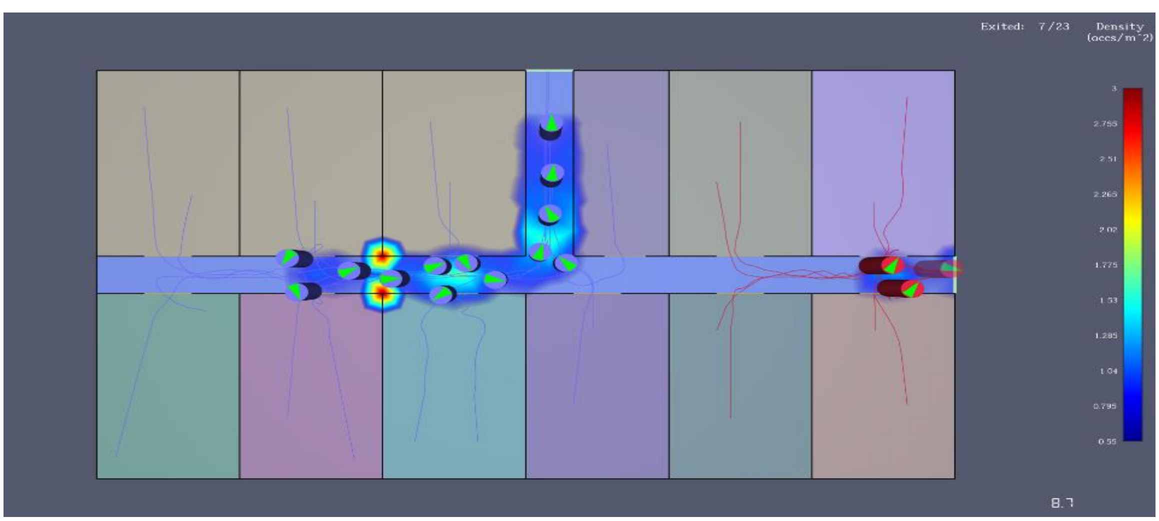
Table 5.5 shows the required time to exit the simulation, via both right and left exits.

IMO 10	MODE	First exiting (s)	Last exiting (s)
	Steering	2.9	22.5
	Steering+SFPE	2.9	29.6
	SFPE	2.2	21.5

Table 5.5: IMO 10 test results

The results for all simulator modes indicate that the four occupants exited via the secondary exit. Figure 5.25 shows trace of occupant paths and density levels of the model in all modes.





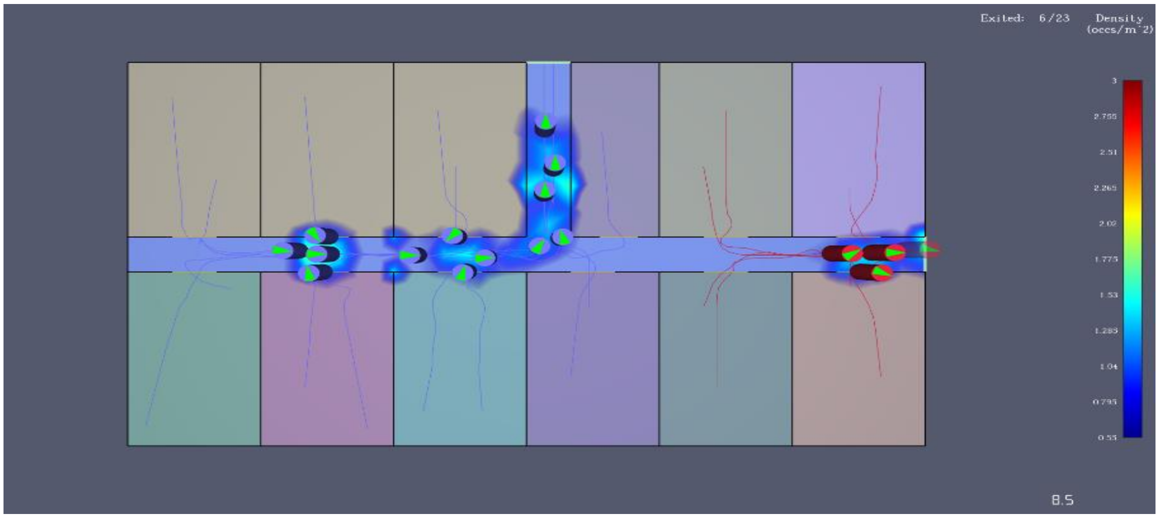


Figure 5.25: Trace of occupant paths and density levels: (i) SFPE (ii) SFPE + Steering (iii) Steering mode

5.9 Congestion (IMO_11)

<u>Description:</u>

The 11th test examines the creation of congestion in Pathfinder. It is based on Test 11 given in MSC.1/Circ.1533 /Annex 3. 150 occupants are uniformly distributed in a 5X8-meter room and via a 12X2-meter corridor they walk up a 5.7X2-meter stairway, exiting the simulation via a 2-meter wide platform. Congestion is expected to form initially at the entrance to the corridor, as well as at the base of the stairs. Figure 5.26 shows the problem setup of simulation test 11.

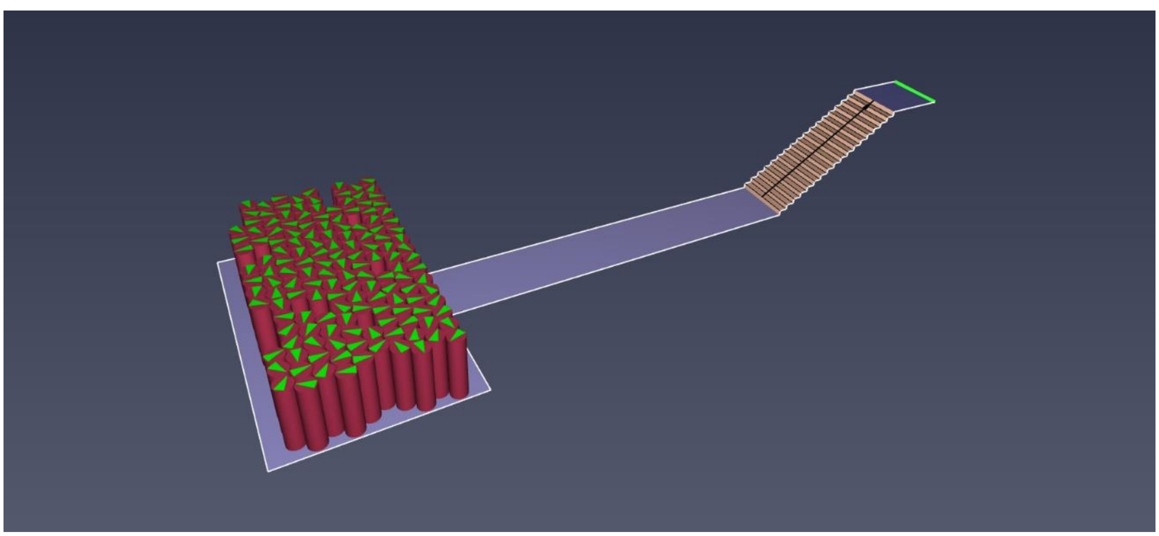


Figure 5.26: IMO_11 problem setup

Setup Notes:

The occupants' profile is one of the IMO proposed ones, as occurred by MSC.1/Circ.1533/Annex 2. The profile is formed by males 30-50 years old, with walking speeds of uniform random distribution and a range of [0.97 m/s, 1.62 m/s]. On stairs-up, the speed is a uniform speed distribution ranging from 0.47 m/s to 0.79 m/s. Figures 5.27 and 5.28 show the Normalized speed-density profile for 30-50-year-old males on level corridor and on stairs up, respectively.

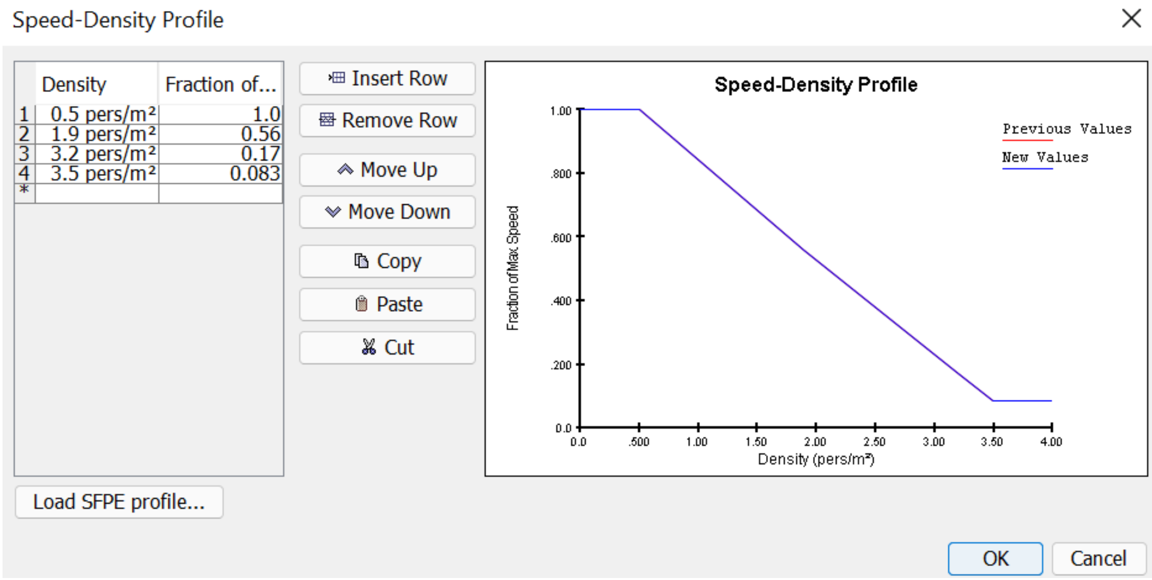


Figure 5.27: Normalized speed-density profile for 30-50-year-old males on level corridor.

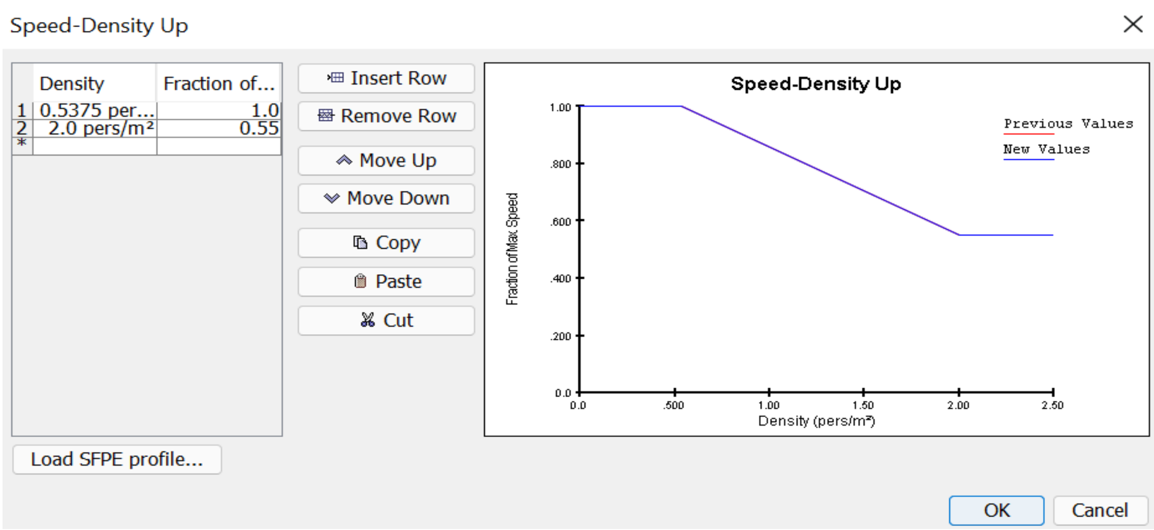


Figure 5.28: Normalized speed-density profile for 30-50-year-old males on stairs up

Expected Results:

Congestion should form in the corridor on the way to the stairs. It is measured by the mean density and mean velocity of the occupants in a 2X2 -meter rectangle at the base of the stairs.

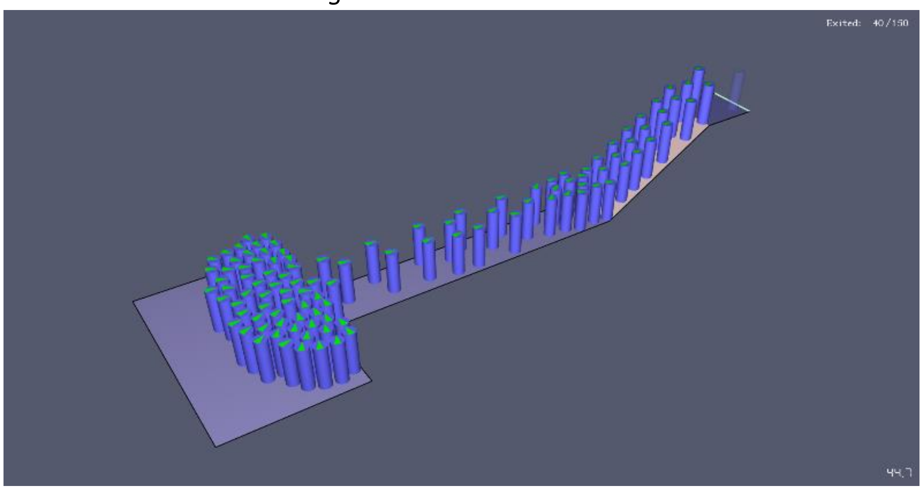
Simulation Results:

Table 5.6 shows the required time to exit the simulation with each of 3 modes. 'First exiting' indicates the first occupant's exiting time and 'Last exiting' shows the last occupant's exiting time.

	MODE	First exiting (s)	Last exiting (s)
IMO 11	Steering	18.8	158.9
	Steering+SFPE	20.3	154.4
	SFPE	24.6	116.4

Table 5.6: IMO 11 test results

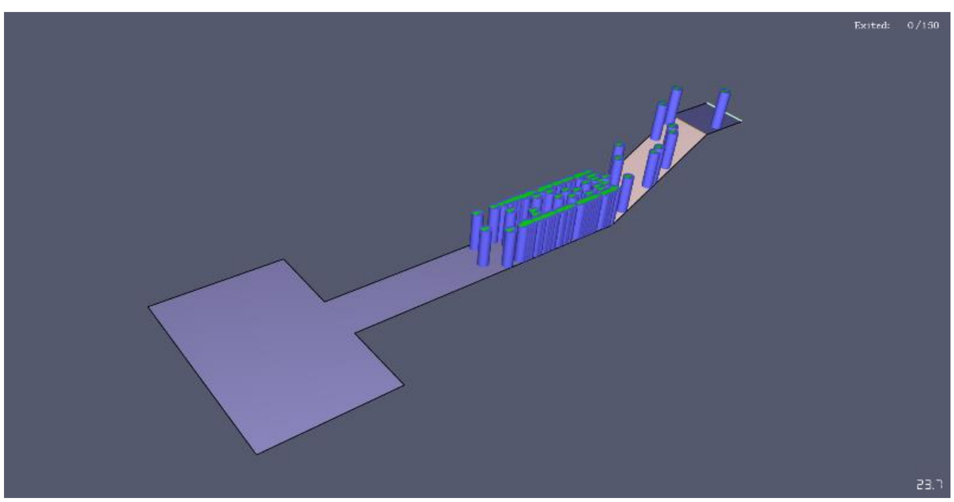
Figures 5.29 and 5.30 show the congestion at the entrance of corridor & at the base of stairs in SFPE and Steering modes, whereas Figure 5.21 shows the density contour of congestion in the same areas in SFPE+Steering mode.



(a) Steering mode

Figure 5.29: Visual demonstration of congestion at entrance of corridor & base of stairs

(b) SFPE mode



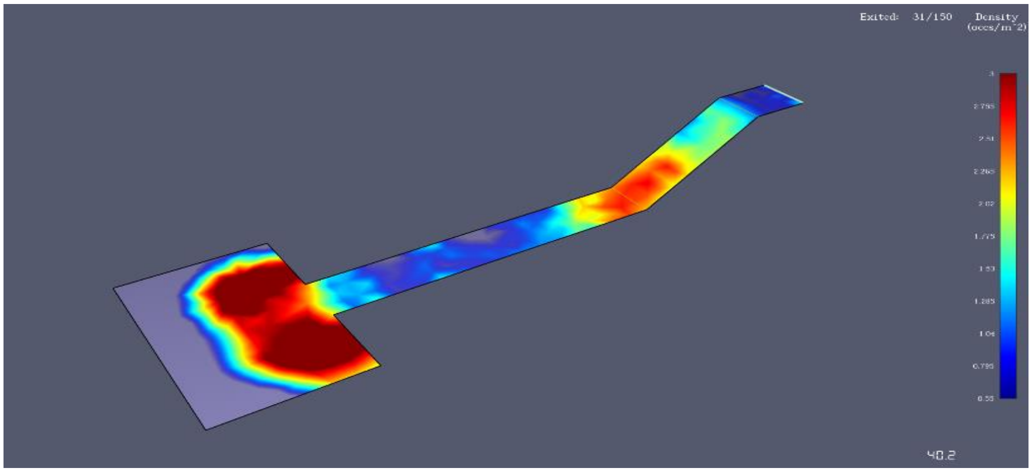


Figure 5.30: Density contours showing congestion at the entrance of corridor & base of stairs

Time history data describing the flow rates, the mean density and the walking speeds for the occupants at the entrance of corridor and base of stairs are shown in Figure 5.31 and 5.32:

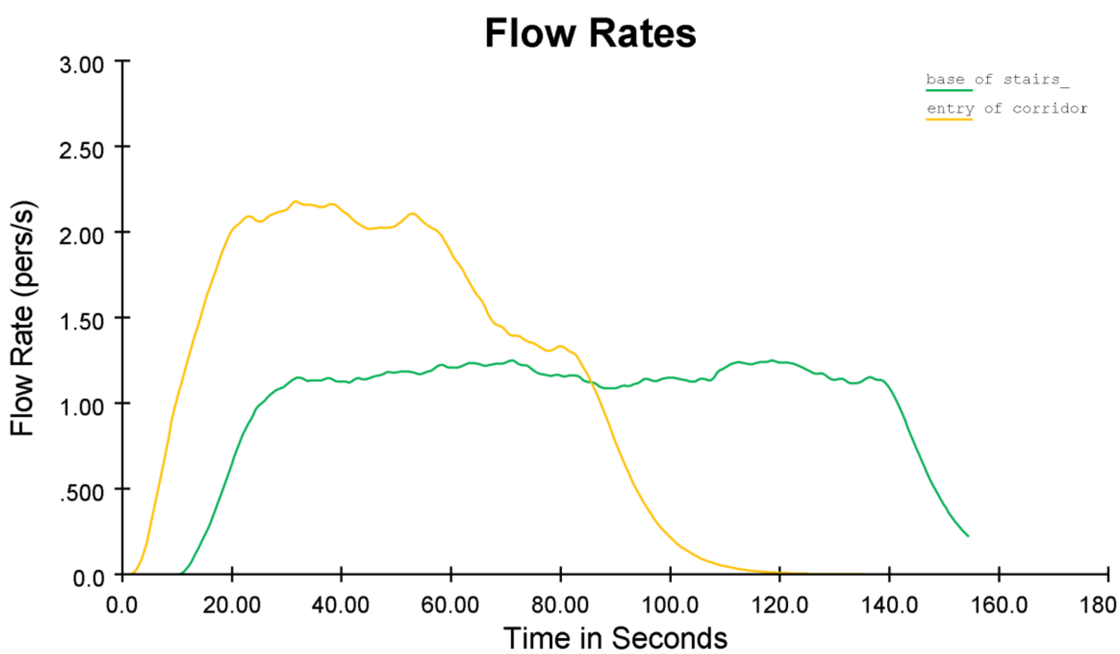


Figure 5.31: Comparison of flow rates at the entrance of corridor & base of stairs

The flow rate through the entry of the corridor has an increasing tendency initially, where the maximum flow rate of about 2.25 pers/s is reached. This high value is steadily decreased as a matter of transferring this congested flow to the base of the stairway, with a steady rate, through the corridor. The latter is concluded by the very stable flow rate of about 1.25 pers/s of the base of the stairway, across the total time walked on it.

Concludingly, the congestion is transmitted to the base of the stairs smoother and more lasting, due to the corridor existence, working exactly like a hydraulic model.

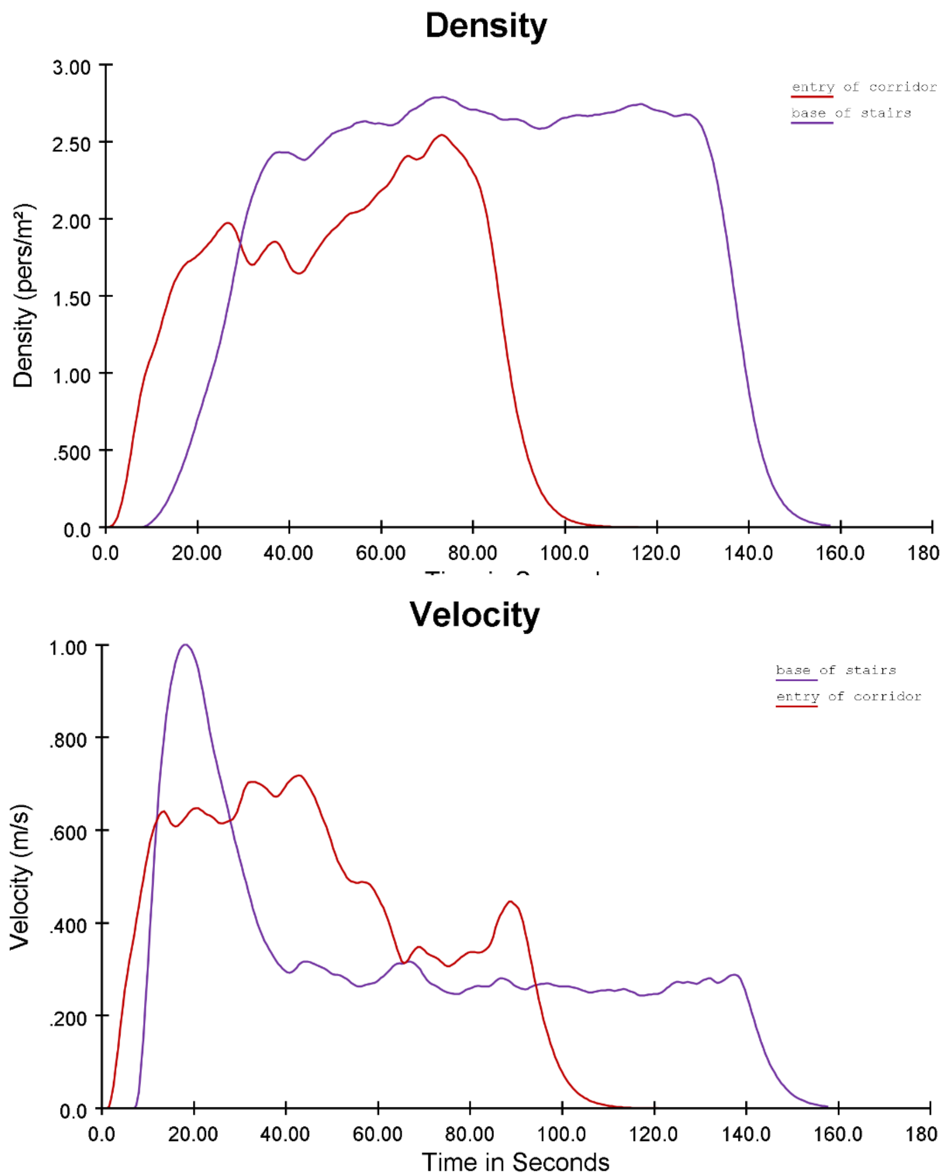


Figure 5.32: Comparison of density and walking speeds at the entrance of corridor & base of stairs

The occupants move through the entrance of the corridor towards the exit with a mean speed of 0.5 m/s and the maximum density is about 2.5 pers/m^2. Moving across the base of the stairway, the mean speed gets even lower, about 0.25 m/s, while maximum density is about 3 pers/m^2.

So, congestion forms initially at the entrance of the corridor, escalating until the end of the corridor, where the base of the stairway is, with even harsher quantitative conditions. This is concluded by comparing the congestion parameters (density and walking speeds) through the occupants way to exit.

In addition, a simulation identical to test 11 model but without stairs is run. Time history data describing the mean density and the walking speeds for the occupants at the base of stairs with and without stairs are also shown in the Figure 5.33:

Congestion at stairs

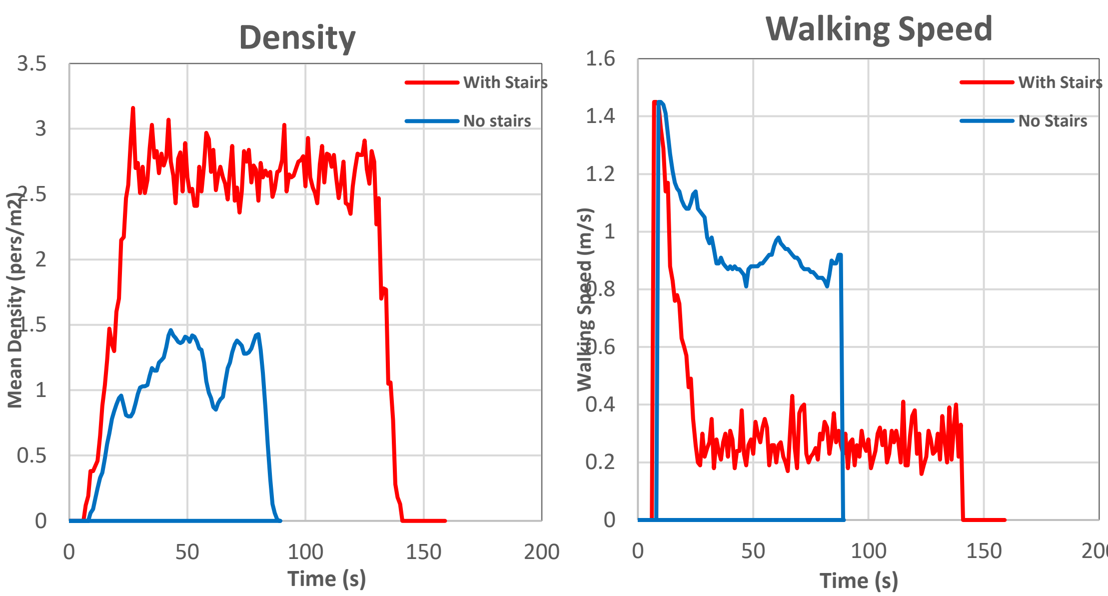


Figure 5.33: Comparison of density and walking speeds at base of stairs with and without stairs

Without stairs, the occupants move to the exit with a mean speed of 1 m/s and the maximum density is about 1.5 pers/m^2. With stairs, the mean speed drops to about 0.25 m/s, while maximum density is about 3 pers/m^2.

As a result, congestion forms at the base of the stairs, as well. This is concluded by comparing the mean density and walking speeds at the base of the stairs for cases with and without stairs.

6 Analysis of Passenger Cabin Evacuation

6.1 Import Geometry and Modify

The evacuation simulations take place in a model, that needs to be created, initially, in Pathfinder. Image formats or CAD files are supported for import, containing the drawing that will be the template for the simulation map construction (e.g. cabins, exit doors). This drawing (DWG) format file is a 2D-floor drawings top-view passenger deck model designed by Autodesk AutoCAD software, shown in Figure 6.1. Importing it to Pathfinder and running various commands and modifications, the 2D model transforms into a 3D model by moving each deck in an appropriate way as shown in Figure 6.2. The imported file assists also the creation of the navigation mesh of the model; making this process significantly user friendlier and more precise.

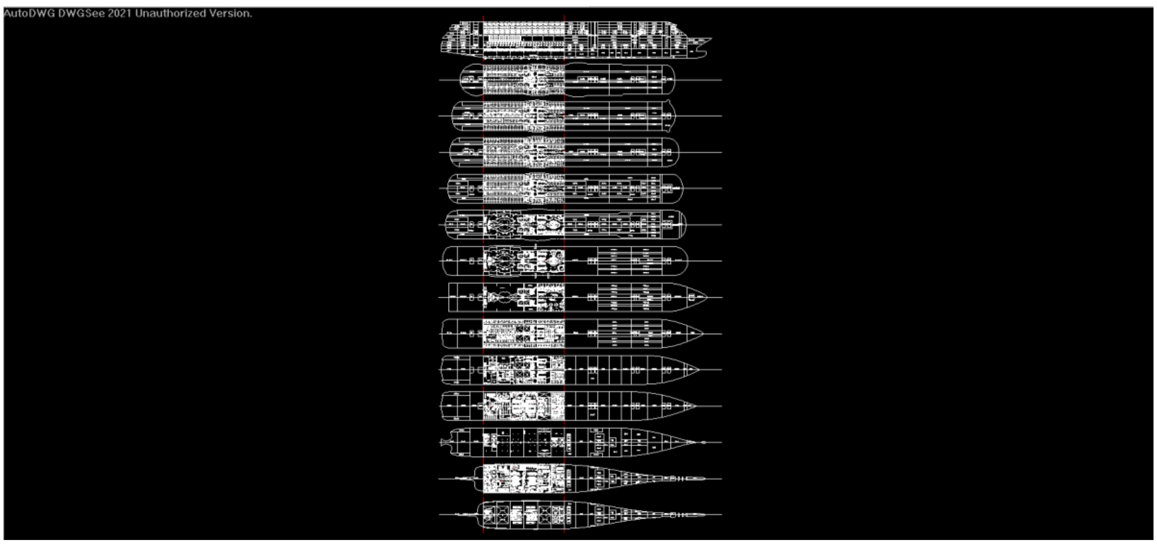


Figure 6.1: DWG top view passenger deck model drawings

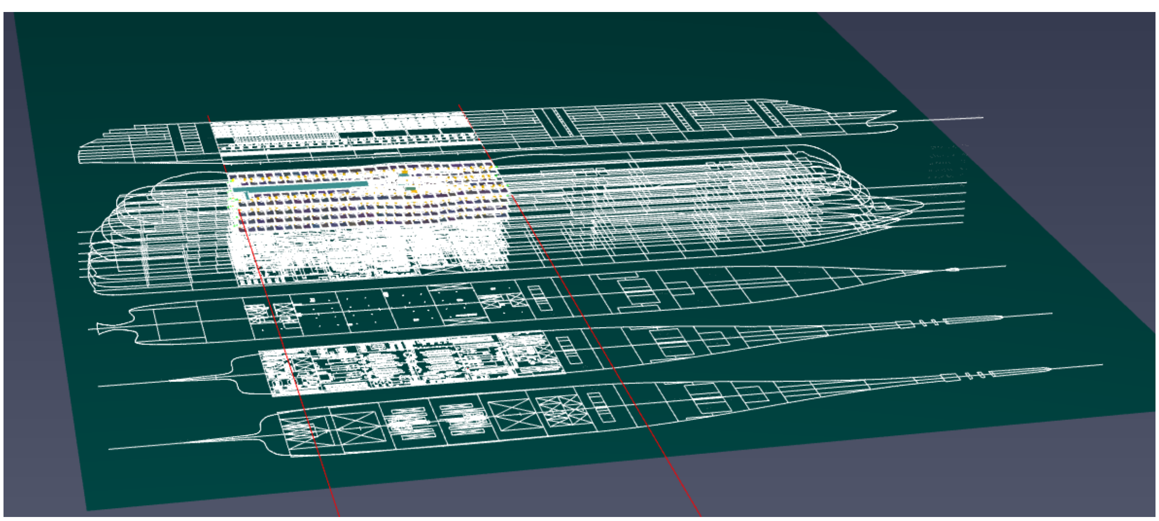


Figure 6.2: Import Drawing and Edit

Next comes the design of the basis on which the levels will be placed. Each of the spaces that make up each level is called Room. The command “Extract room from imported geometry” is used for the visualization of rooms for complex geometries. For the output of a room using this command, the surface on the desired room is selected, and then the program generates that room by bounding the lines of the drawing that surrounds that surface.

The ship geometry of Papadakis (2020) was used for our evacuation simulations.

6.2 Cabin Spaces Features

Model geometry

The initial drawing on which the analysis will be based on corresponds to a fictitious but plausible form of a cruise ship divided into vertical fire zones (MVZ). These areas are chosen as they represent the majority of the areas on which passengers and crew are exposed to a certain emergency situation (e.g. The area of each deck to be designed (decks 6,7,8,9) shall consist of two main zones and shall have the following dimensions:

- total length of both MVZ: 87 m
- total width of both MVZ: 32 m
- total area of both MVZ: 2872 m^2

The net heights of the decks are:

- Deck 6: 2.7m
- Deck 7: 2.7 m
- Deck 8: 3.35 m
- Deck 9: 2.7 m

Each deck has two corridors which do not communicate with each other. The minimum width of the corridors is 1m, fulfilling the requirement of the International Code for FSS for minimum corridor width of 0.9 m.

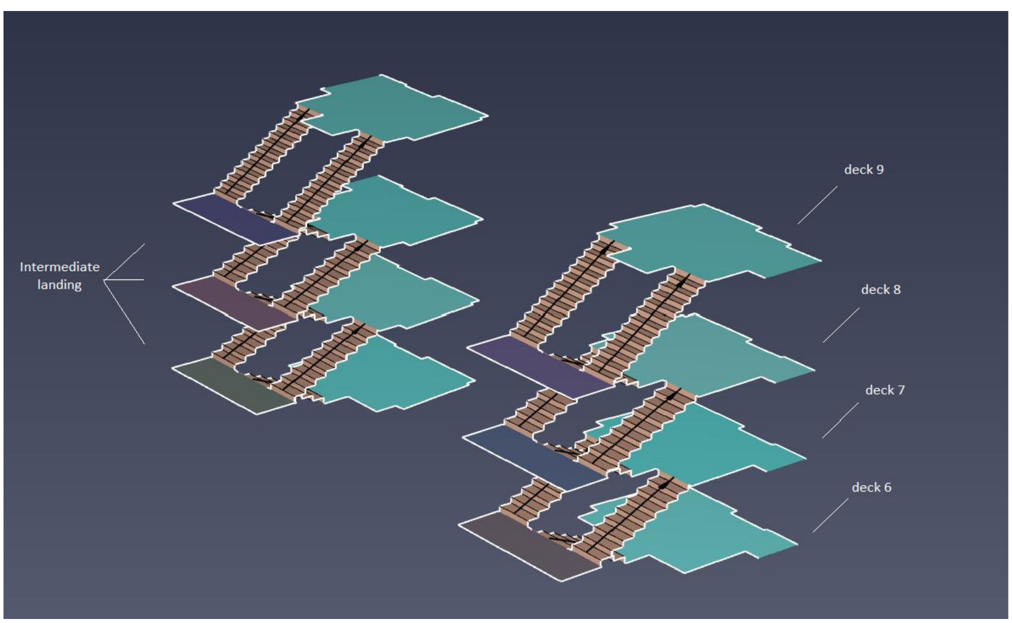


Figure 6.3: Staircase form

The various decks communicate with each other through two staircases connecting the corridors of each deck. The stairways have the form Y, i.e. there is one entry path to and two exit paths from them. In the middle of each stairway there is an intermediate space (intermediate landing) connecting these two paths as shown in Figure 6.3. It is worth noting that there are differences in areas between the cabins. The minimum area they occupy is 12 m^2 for the cabins for two and 20 m^2 for the cabins for four passengers. Even the minimum width of each door is 0.75 m. Figure 6.4 shows a typical form of cabin areas.

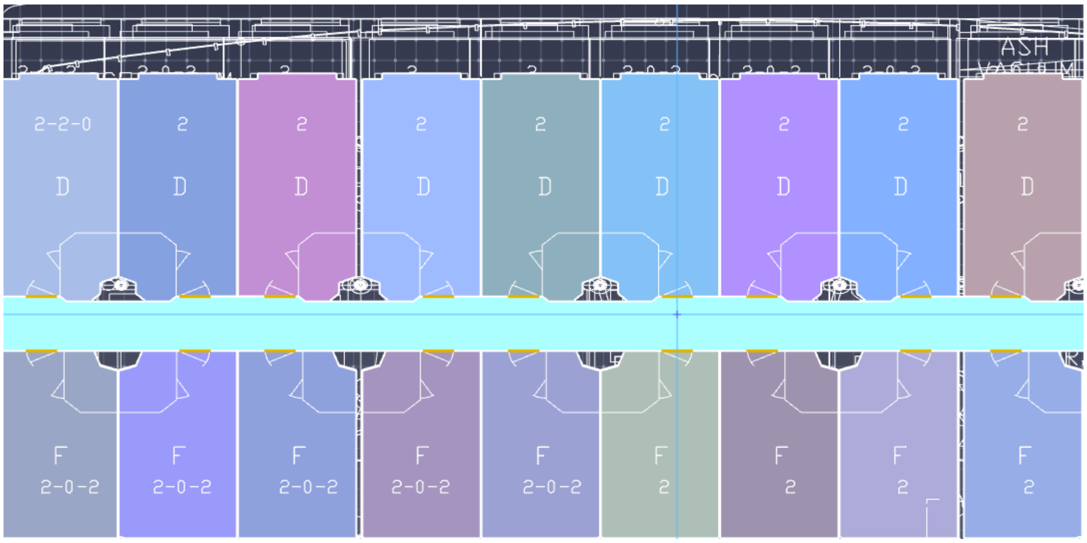


Figure 6.4: Typical Cabins form

6.3 Exit Doors Locations

There are four emergency exits in each deck (16 totally) placed at the boundaries of each deck on the x axis. Their name is important for understanding the problem, as we will create evacuation cases with some of them disabled. After an occupant crosses an exit door, his is considered safe and is heading directly to the assembly station where embarkation to lifeboats takes place.

Each one is identified with:

- 6, 7, 8 and 9 depending on the deck located for the Z axis,
- A (Aft) and F(Fore) for its position on the X axis
- P (Port) and S (Starboard) for its position on the Y axis.

DECK 6	DECK 7	DECK 8	DECK 9
6 AS	7 AS	8 AS	9 AS
6 AP	7 AP	8 AP	9 AP
6 FS	7 FS	8 FS	9 FS
6 FP	7 FP	8 FP	9 FP

Table 6.1: Cabin decks exit doors

It is worth noting that we have not regulated the exits of individuals, i.e. when evacuating, occupants can use whichever exit they want to escape. Figure 6.5 shows the topside of the four decks, with their corresponding exit door locations.

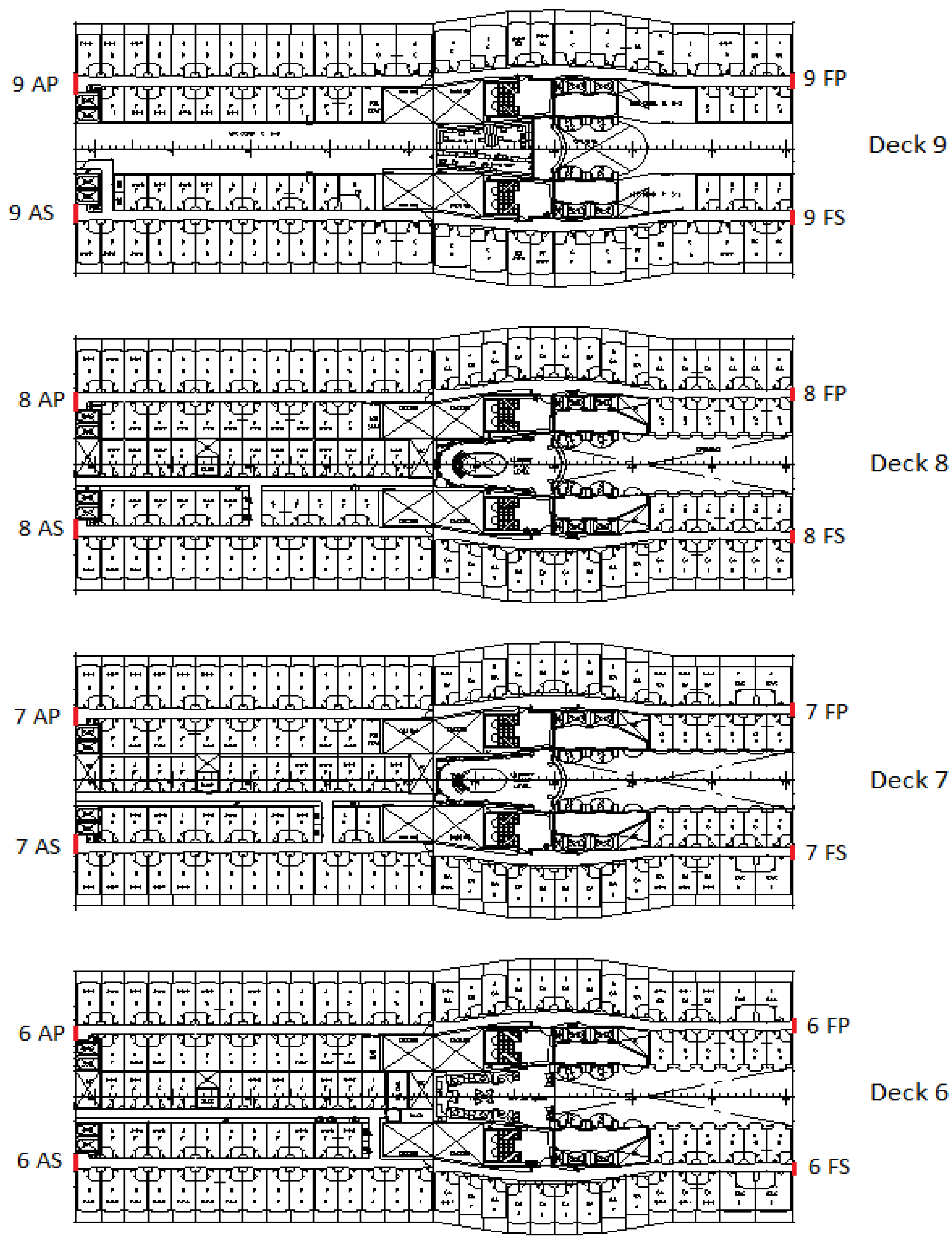


Figure 6.5: Exit doors locations for each deck

6.4 Population Features

The total population in the simulations will be 838 divided not uniformly in each deck, as a result of having 2-person and 4-person cabins in different proportions and numbers as shown below. Furthermore, "IMO Males 30-50 years old" profile has been used for all cases of the analysis, as well as the Steering mode to control passenger movement.

	Cabins for 2	Cabins for 4	Passengers
Deck 6	99	4	214
Deck 7	100	4	216
Deck 8	106	0	212
Deck 9	64	17	196
Total	369	25	838

Table 6.2: Distribution of population in cabin decks

6.5 Cases of Sensitivity Analysis

Going on the part of the sensitivity analysis of the evacuation time, a basic model is to be studied as a nominal one, with the following main parameters:

- ✓ Day case
- ✓ Cabin areas with 100% capacity (838 occupants)
- ✓ Evacuation way to any exit of every occupants' preference
- ✓ Analysis of all four cabin decks (6,7,8,9) with every exit door available
- ✓ Occupants profiles are based on IMO "Males 30-50 years old"

To examine the sensitivity of the evacuation time, a set of scenarios is considered, the parameters of which are determined by the influence of the following factors on their total:

- ➢ Environmental factors: i.e. the ship heeling in case of water inflow, but also smoke and fire inside the ship that affects the visibility and the movement of passengers and the availability of the exit doors, as well.

- ➢ Human factors: i.e. passenger behavior, which is not taken into account in the IMO guidelines or is greatly simplified.

Therefore, the scenarios for this sensitivity examination will include some variables that affect parameters of the evacuation process such as movement speed and decision-making ways. The variables that will be considered in the simulation model are the following:

- inclination of the ship → Affects the speed of movement of passengers
    - Ship heeling
        - 10˚-20˚ angles scenario

- Fire and smoke → Reduction of visibility, affects the movement speed of passengers and their decision-making, as many times the smoke can limit the choice of exits availability. It will not, however, affect the death of people due to toxic substance release or heat.
    - Reduced visibility of passengers:
        - Medium visibility reduction scenario
        - Harsh visibility reduction scenario
    - Limited availability of exit doors
        - 12.5% less available exit doors
        - 50% less available exit doors
        - 75% less available exit doors

Panic as a characteristic of a person's behavior → Effect on speed of movement and decision making.

- Panic behavior of occupants
    - 5% passengers in panic
    - 20% passengers in panic
    - 40% passengers in panic

Five (5) different scenarios of this model are being analyzed below, with their particular subcases each, as mentioned above:

1. Normal scenario
2. Ship heeling angle
3. Reduced visibility of occupants (due to factors e.g. non-irritant wood smoke)
4. Limited availability of exit doors (due to factors e.g. fire)
5. Panic behavior of occupants

In addition, three (3) combined scenarios of this model are also analyzed, to examine whether their evacuation time affection is an algebraic summing up of each individually or not, compared to the normal scenario. The cases are:

1. Limited availability of exit doors & ship heeling
2. Limited availability of exit doors & visibility reduction
3. Limited availability of exit doors & occupants in panic

6.5.1 Normal Scenario

Description:

The normal scenario applies all the main parameters as described above, and is used for our sensitivity analysis as the nominal case. Its output values will be yardsticks for the rest of the scenarios, to qualify and quantify the extent of influence of the modification of several parameters to the ship evacuation.

Setup notes:

The common profile of the total of occupants is "Male 30-50 years old" based on IMO, with movement speeds, shoulder width, and all the rest specifications as mentioned in chapter 4.2: *Pathfinder simulation parameters*. The behavior is the "Day case", common for all the occupants. It includes an initial delay that depends on the day case function of chapter 4.2.5: *Initial delay*.

Results:

The total evacuation time of the scenario was 287.4 s. Figure 6.6 presents the total percentage of occupants evacuated as a function of the evacuation time.

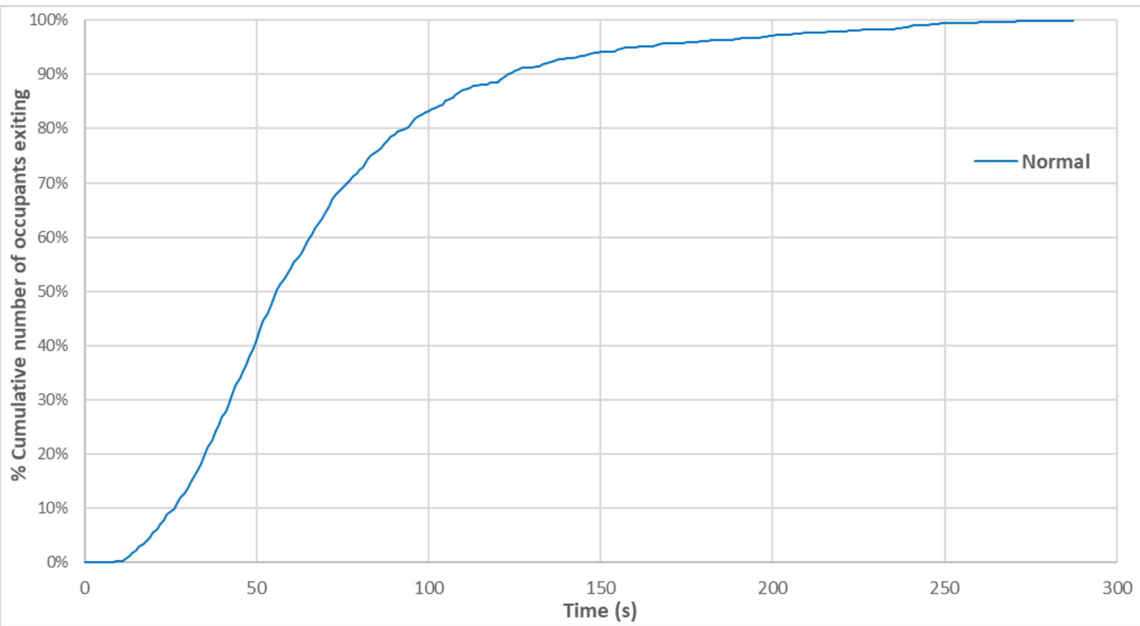


Figure 6.6: Cumulative number of occupants exiting (%), normal case

The general results of the simulation are presented on the Table 6.3:

	First exiting (s)	Last exiting(s)	Average exit time (s)	Minimum travel distance(m)	Maximum travel distance(m)	50% occupants exited (s)	75% occupants exited (s)	90% occupants exited (s)
NORMAL	6.4	287.4	68.2	3	77.9	55.7	83	123

Table 6.3: General results, normal case

Exit doors results are presented in the Appendix, in Tables 6.4, 6.6, 6.8, 6.10 and 6.12 for all the scenarios of the analysis.

6.5.2 Ship Heeling Angle Scenario

Description:

Static inclination of a ship, is the one that the angle of the ship is constant with respect to time. Heel is called the transverse one, and according to Valanto (2006) it has been established that the ship shall capsize if the heel angle exceeds 30˚. Sun et al. (2017) on their study, presented the effect of the heel angle of the ship at the movement speed of the occupants, as shown in Figure 6.7.

In the current study the actual heel angle is considered in the range [0˚,20˚]. The ship heel direction, e.g. heel right or left (Figure 6.8) does not affect the final movement speed of occupants, whereas the movement direction of the occupant does not affect the degree of their speed reduction, as either they move heel up (positive angles) or heel down (negative angles), the degree of their speed reduction remains constant. As a result of the above, we study the case of a [10˚,20˚] range heel. On this case, there is a 4.5% reduction to the movement speed of each occupant.

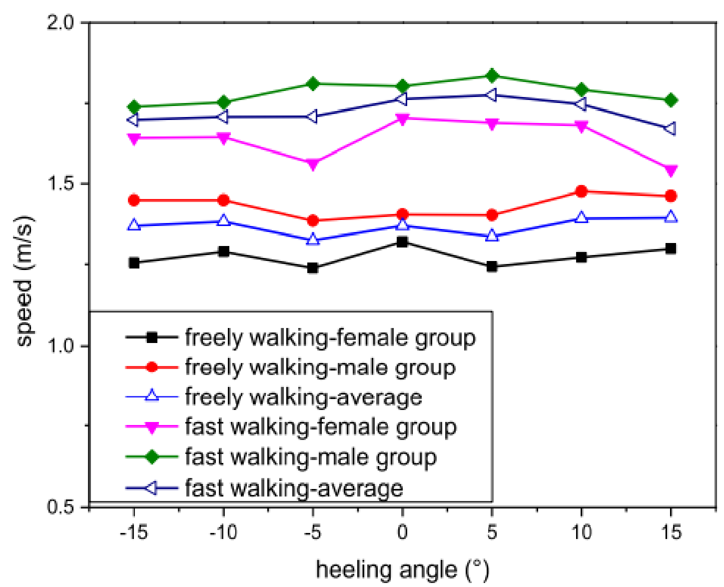


Figure 6.7: Degree of effect of heel inclination on the basic speed of the passengers (sun et al. 2017)

Figure 6.8: ship heeling types (Kotsakis, 2021)

Setup notes:

The setup notes are identical to the normal scenario, except for the profile of the occupants that now is “Males 30-50 years old 15˚” common for all. The case is run with the average data of its particular range, so 15˚. The only difference to the nominal one is the movement speed, that is 4.5% reduced. So, the global movement speed is a uniform distribution with a minimum of 0.92635 m/s and a maximum of 1.5471 m/s. The reduction factor applies automatically to the slopped terrains, too.

Results:

The total evacuation time of the scenario was 291 s. Figure 6.9 presents the total percentage of occupants evacuated as a function of the evacuation time, in comparison to the nominal case, as well.

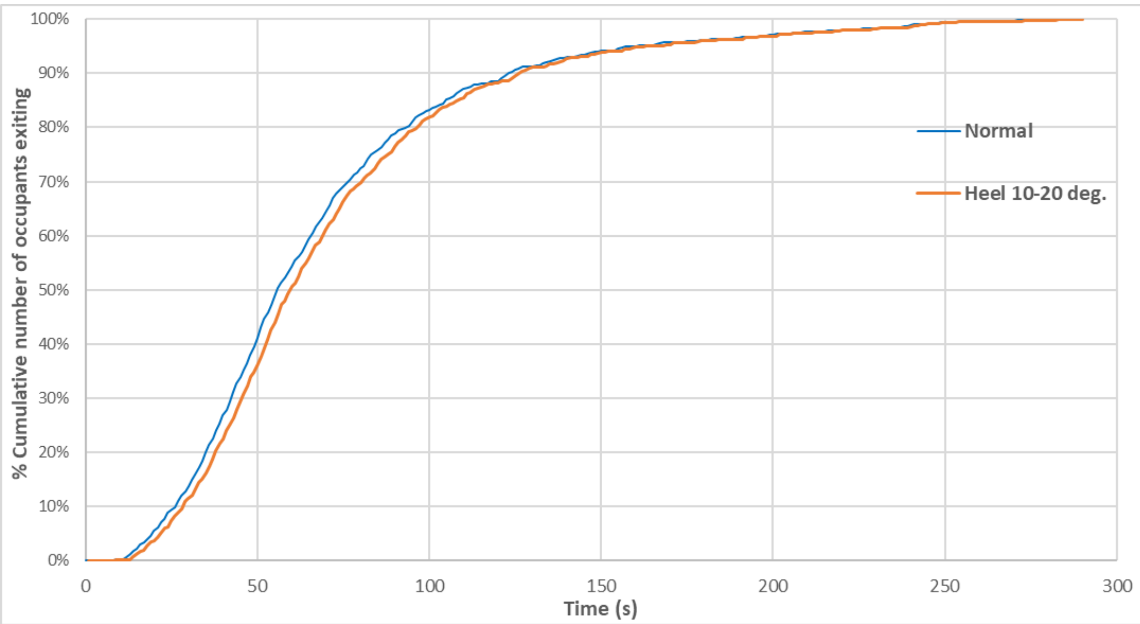


Figure 6.9: Cumulative number of occupants exiting (%), ship heeling case

The general results of the simulation are presented on the Table 6.5:

HEEL 10˚ -20˚	First exiting (s)	Last exiting(s)	Average exit time (s)	Minimum travel distance (m)	Maximum travel distance(m)	50% occupants exited (s)	75% occupants exited (s)	90% occupants exited
	6.4	291	69.4	2.5	77.5	57.5	86	124
INCREASE FROM NORMAL (%)		**1.25%**	**1.8%**		**- 0.5%**	**3%**	**4%**	**0.8%**

Table 6.5: General results, ship heeling

Comments:

The 1.25% (+3.6 seconds) increase of the evacuation time of this scenario compared to the normal one, is attributed to the 4.5% reduced movement speed of all the occupants. The initial delays remain the same in heel scenario, as well as the flow rate that does not exceed the value of 2 pers/sec. The evacuation rate of the occupants is just slightly lower during the range 25-100 seconds of the evacuation, but generally keeps an almost identical trajectory compared to the nominal case, according to Figure 6.9.

6.5.3 Reduced Visibility Scenario

Description:

A fire accident significantly affects the movement speed of individuals. Due to smoke occurring on such accident can reduce the visibility of the occupants during the evacuation process, impeding even dramatically sometimes their process of exiting. The degree of visibility reduction is correlated to an extinction coefficient: It is an intrinsic feature of chemical elements that depends on their chemical composition and structure. The SI units of the coefficient are m^2 /mol, but in practice is usually taken as m^{-1} or cm^{-1}. Indicates the measure of how intensively a substance absorbs light at a specific wavelength. In many publications the term visibility (Optical density) is used in units OD/m^{-1} or OD/cm^{-1} but it is the same.

Koromila et al. (2020) on a study, researched the effect of smoke obscuration in walking speed. As we can see in the graph, the scale of optical density can split in three ranges: [0-0.2], [0.2-0.4] and [0.4-0.6] OD/m^{-1}. We focus on the impact of reduced visibility of occupants may have on the evacuation time as well as the extent of it in its different intense.

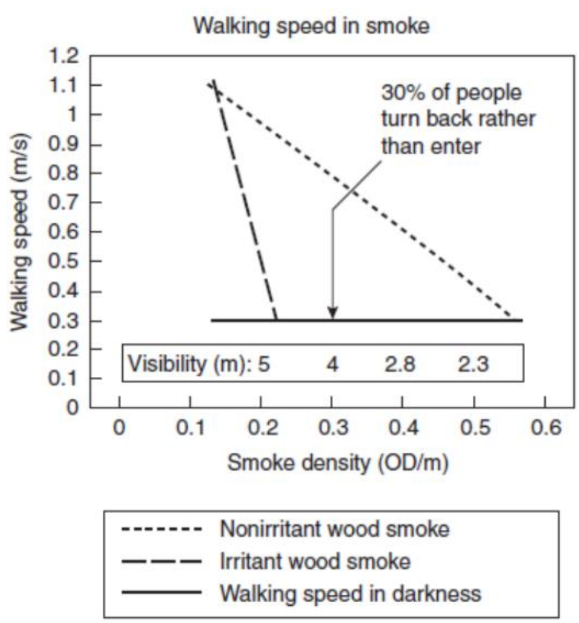


Figure 6.10: Occupants speed reduction as a function of optical density, Koromila et al. (2020)

Thus, we study two crucial subcases:

I. Medium visibility reduction
   - [0.2-0.4] OD/m^{-1}
   - ≈ 4m visibility
   - 43% movement speed reduction

II. Harsh visibility reduction
   - [0.4-0.6] OD/m^{-1}
   - ≈ 2.3m visibility
   - 71% movement speed reduction

<u>Setup notes:</u>

The setup notes are identical to the nominal case, except for the profile of the occupants that is:

I. "0.3 OD/m^{-1}" for the Medium visibility reduction scenario
II. "0.5 OD/m^{-1}" for the Harsh visibility reduction scenario

Common for all occupants of the simulation, respectively. Each subcase is run with the average data of its particular range. (i.e. 0.2-0.4 with 0.3 OD/m^{-1}, 0.4-0.6 with 0.5 OD/m^{-1})

The only difference of the profiles to the nominal one is the movement speed, that is respectively:

I. 43% reduced
II. 71% reduced

So, the global movement speed is a uniform distribution ranging between:

I. [0.5543, 0.9257] m/s
II. [0.2771, 0.4628] m/s

The reduction factors apply automatically to the slopped terrains, too.

<u>Results:</u>

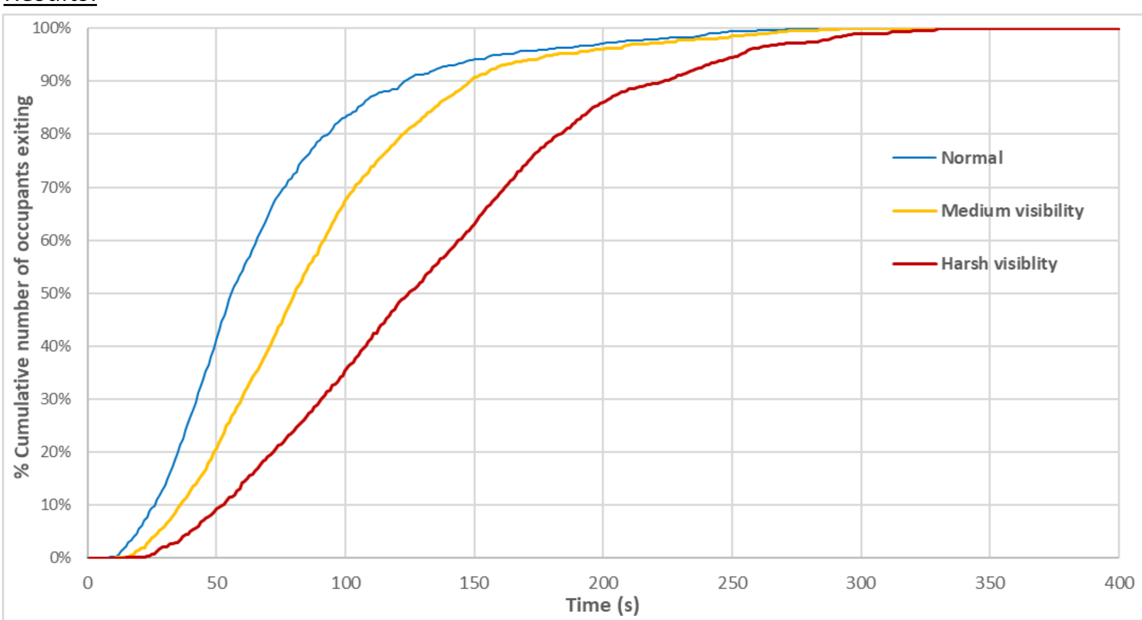


Figure 6.11: Cumulative number of occupants exiting (%), reduced visibility cases

The total evacuation times were 345.2 s and 480.4 s for each subcase, respectively. Figure 6.11 presents the total percentage of occupants evacuated as a function of the evacuation time, in comparison to the nominal case, as well.

The general results of the simulations are presented on the Table 6.7:

Case	First exiting (s)	Last exiting(s)	Average exit time (s)	Minimum travel distance (m)	Maximum travel distance(m)	50% occupants exited (s)	75% occupants exited (s)	90% occupants exited (s)
0.3 OD/m^{-1}	8.1	345.2	87.2	2.7	80.7	78.4	110.4	146.2
INCREASE FROM NORMAL (%)		**20%**	**28%**		**3.6%**	**41%**	**33%**	**19%**
0.5 OD/m^{-1}	12.5	480.4	129.7	2.8	79.1	122.7	169.5	221
INCREASE FROM NORMAL (%)		**67%**	**90%**		**1.5%**	**120%**	**104%**	**80%**

Table 6.7: General results, reduced visibility cases

<u>Comments:</u>

The greater the visibility reduction is, the more the evacuation time is increased. At the medium visibility case 43% global movement speed reduction causes 20% increased evacuation time, (+57.4 seconds), whereas at the harsh visibility case 71% global movement speed reduction causes 67% increase (+193 seconds), in comparison to the nominal case.

The initial delays remain the same as in nominal case, as well as the flow rates that does not exceed the value of 2 pers/sec. The evacuation rate of the occupants is significantly reduced the harsher the visibility reduction is, according to Figure 6.11. There is also noticeable delay in the evacuation process on the average, in both cases. The exit time of 50% of total occupants is 41% and 120% increased to the normal case, respectively. This is also confirmed from the average exit time that is 28% and 90% increased, respectively, too.

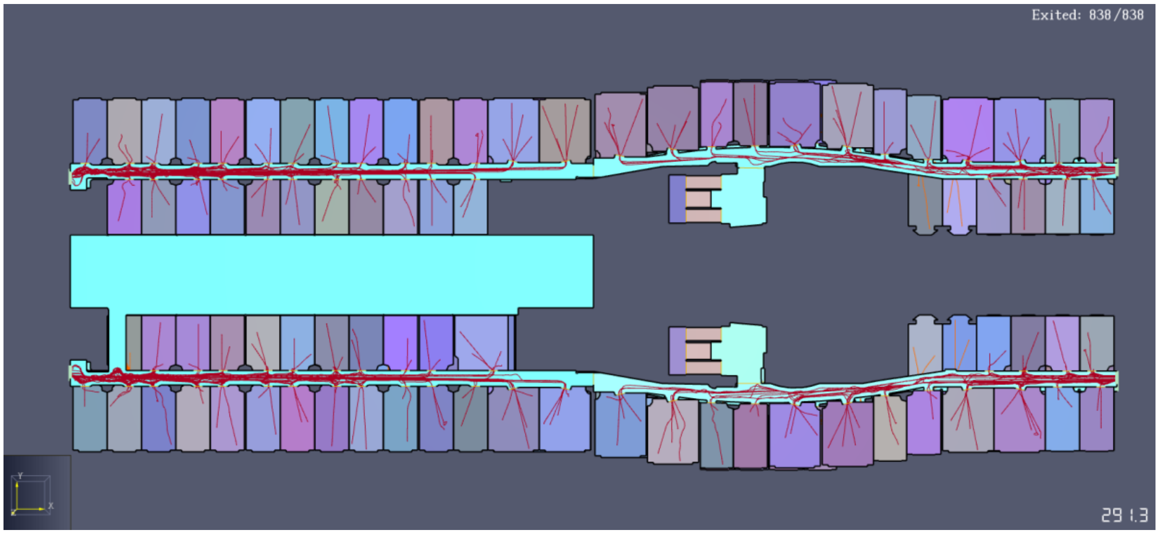


Figure 6.12: Contour plot of medium visibility reduction scenario with occupants' exit paths

6.5.4 Limited Availability of Exit Doors Scenario

Description:

The unavailability of some exit doors of decks in case of a fire accident force several occupants that they intended to exit from those doors to alter their path and choose another exit door of the same, or even of upper decks. We run simulations for three subcases.

I. 12.5% unavailable exit doors (2 out of 16)
   - Half (2) doors of Deck 6 (6 AS & 6 FP out of order)

II. 50% unavailable exit doors (8 out of 16)
   - All (4) exit doors on Deck 6 (6 AS,6 AP,6 FS,6 FP out of order)
   - All (4) exit doors on Deck 7 (7 AS,7 AP,7 FS,7 FP out of order)

III. 75% unavailable exit doors (12 out of 16)
   - All (4) exit doors on Deck 6 (6 AS,6 AP,6 FS,6 FP out of order)
   - All (4) exit doors on Deck 7 (7 AS,7 AP,7 FS,7 FP out of order)
   - Half (2) exit doors of Deck 8 (8 AS & 8 FP out of order)
   - Half (2) exit doors of Deck 9 (9 AP & 9 FS out of order)

Setup Notes:

The setup notes are identical to the normal scenario for all of the three simulation cases. In each simulation, the selected exit doors have been disabled. Furthermore, measurement regions have been added on the staircases of all decks and on the corridors towards the -closer- forward exits of decks 8 & 9, as shown in Figure 6.13. They are placed there, especially, because all occupants from decks 6 & 7 will move to those, causing congestion. These regions count the density (pers/m^2) of the selected are for the total evacuation time.

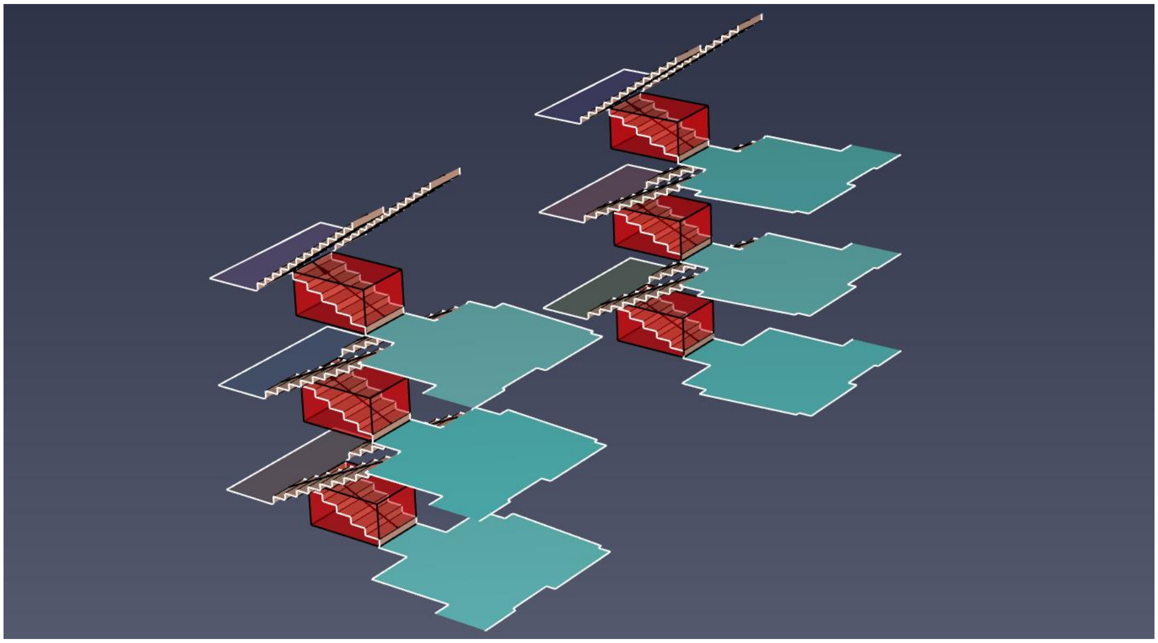


Figure 6.13: Measurement Regions at main stairs of the staircases

<u>Results</u>:

The total evacuation times were 302.5 s, 361.8 s and 483.7 s for subcase 12.5, 50 and 75%, respectively. Figure 6.14 below presents the total percentage of occupants evacuated as a function of the evacuation time, in comparison to the nominal case, as well.

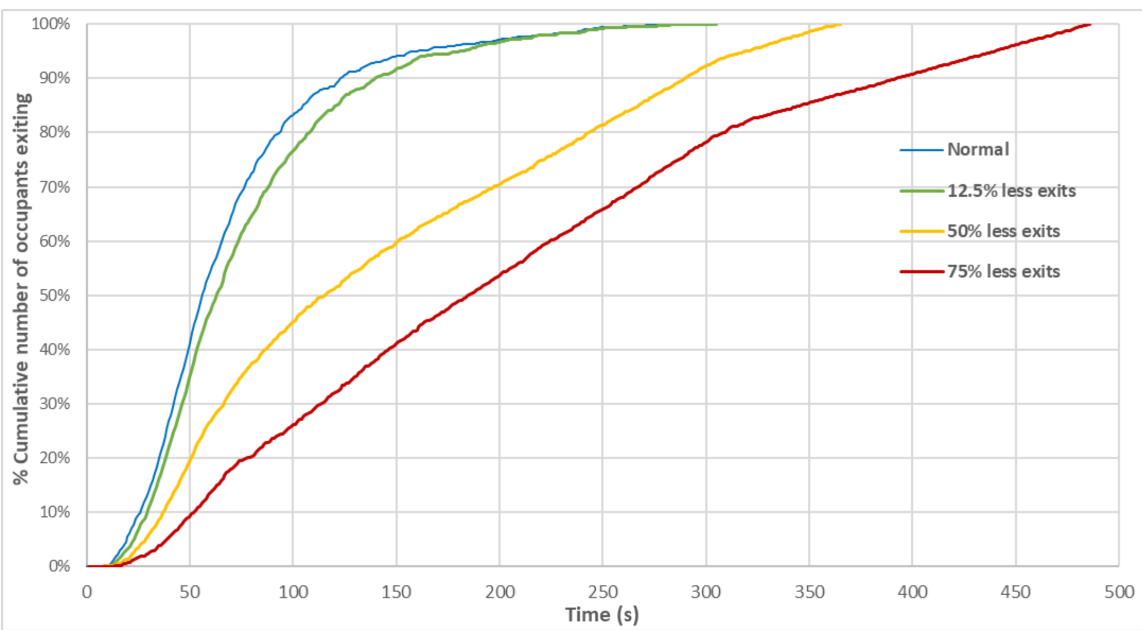


Figure 6.14: Cumulative number of occupants exiting (%), limited availability of exit doors cases

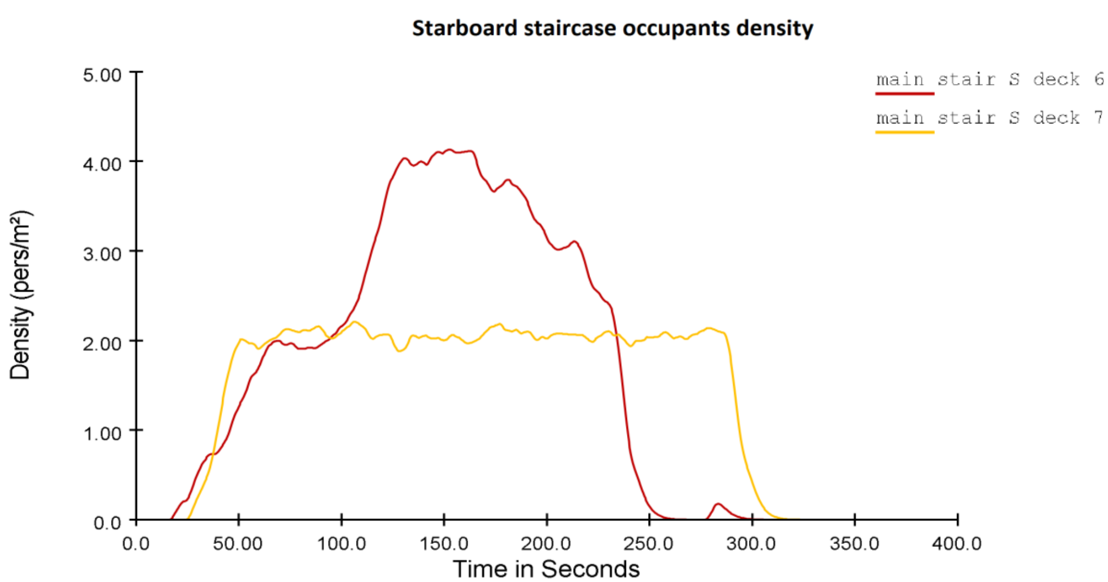
The general results of the simulations are presented on the Table 6.9:

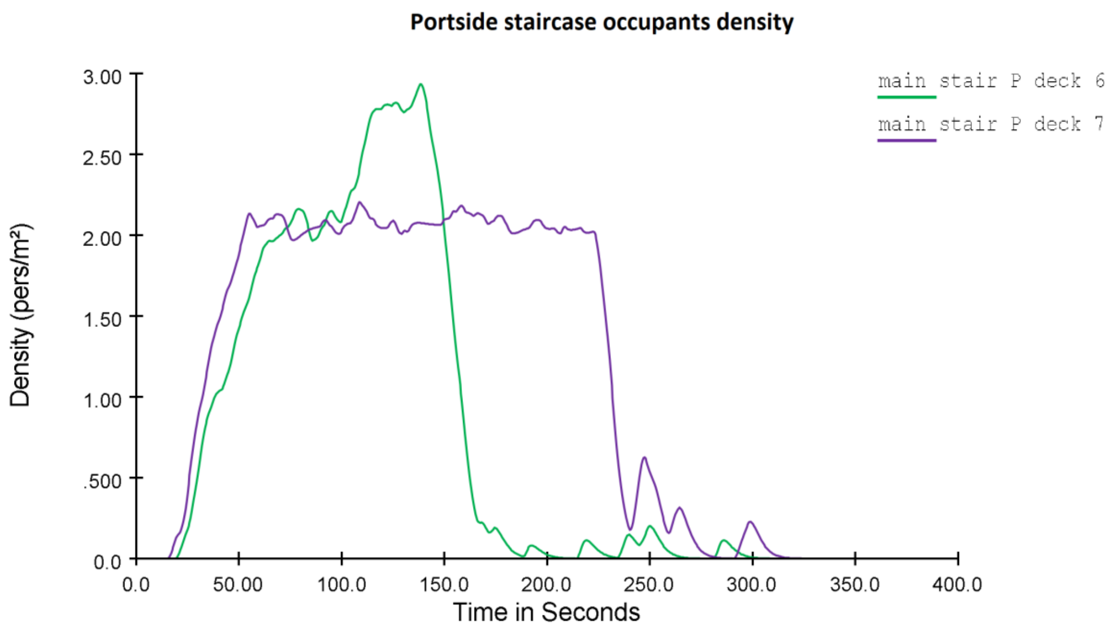
Case	First exiting (s)	Last exiting(s)	Average exit time (s)	Minimum travel distance (m)	Maximum travel distance(m)	50% occupants exited (s)	75% occupants exited (s)	90% occupants exited (s)
2/16 (12.5%)	6.4	302.5	74.1	3	94	60.8	94.8	137.5
INCREASE FROM NORMAL (%)		**5%**	**8.7%**		**21%**	**7.7%**	**14%**	**12%**
8/16 (50%)	6.4	361.8	139.9	3	152	113.2	219.5	287.8
INCREASE FROM NORMAL (%)		**26%**	**105%**		**95%**	**103%**	**164%**	**134%**
12/16 (75%)	11.3	483.7	199.4	3	168.1	182.7	285.7	390
INCREASE FROM NORMAL (%)		**68%**	**192%**		**116%**	**228%**	**244%**	**217%**

Table 6.9: General results, limited availability of exit doors cases

Density graphs and values for portside and starboard staircases as well as corridors at fore exits for both 50% and 75% subcases are presented in Figure 6.15 and 6.16, respectively:

50% less exits (8 out of 16):





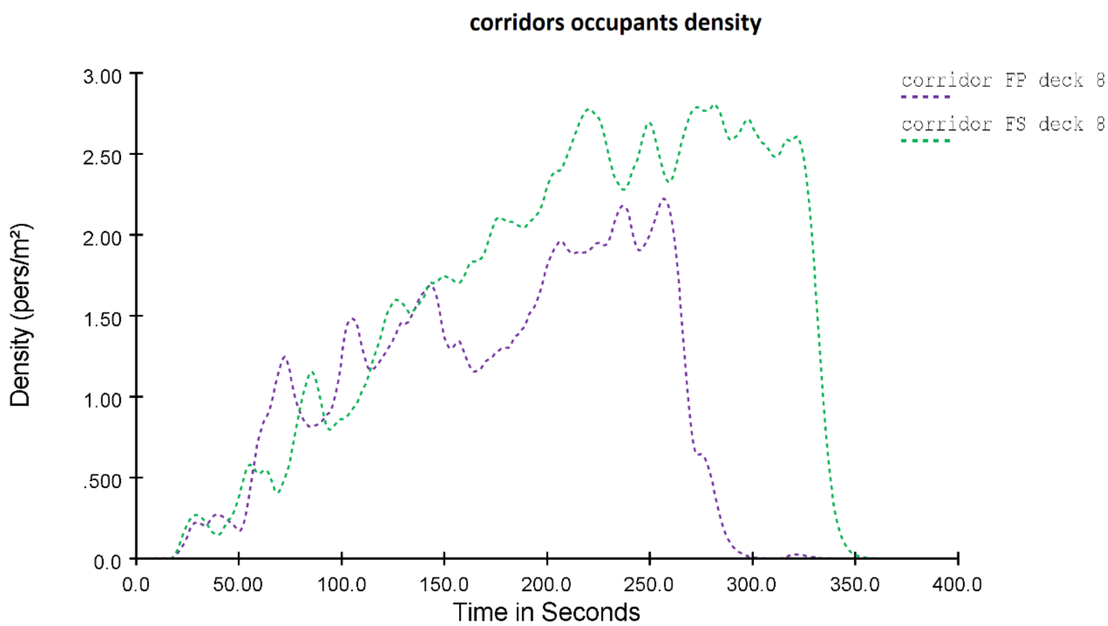
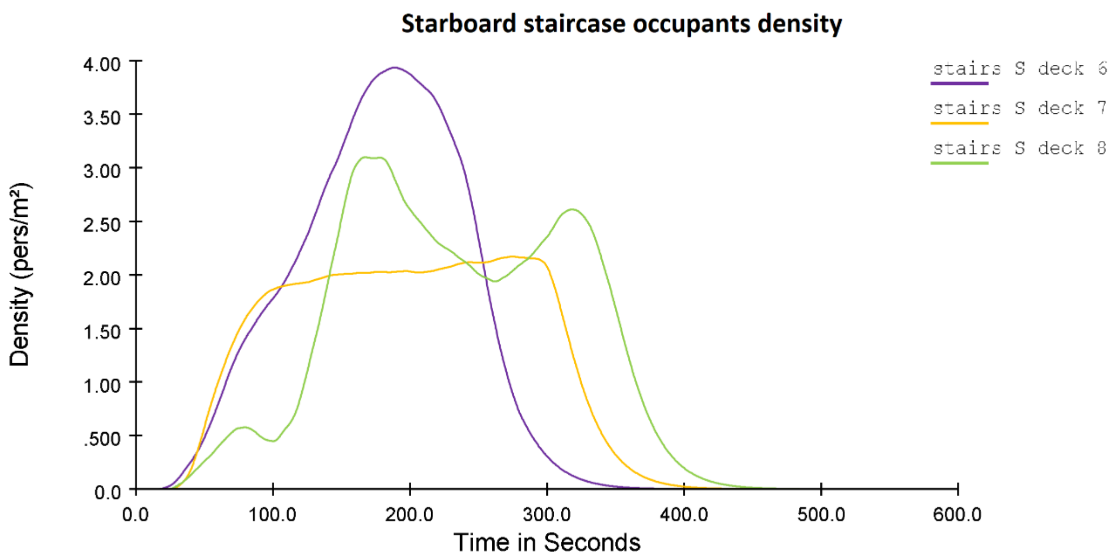
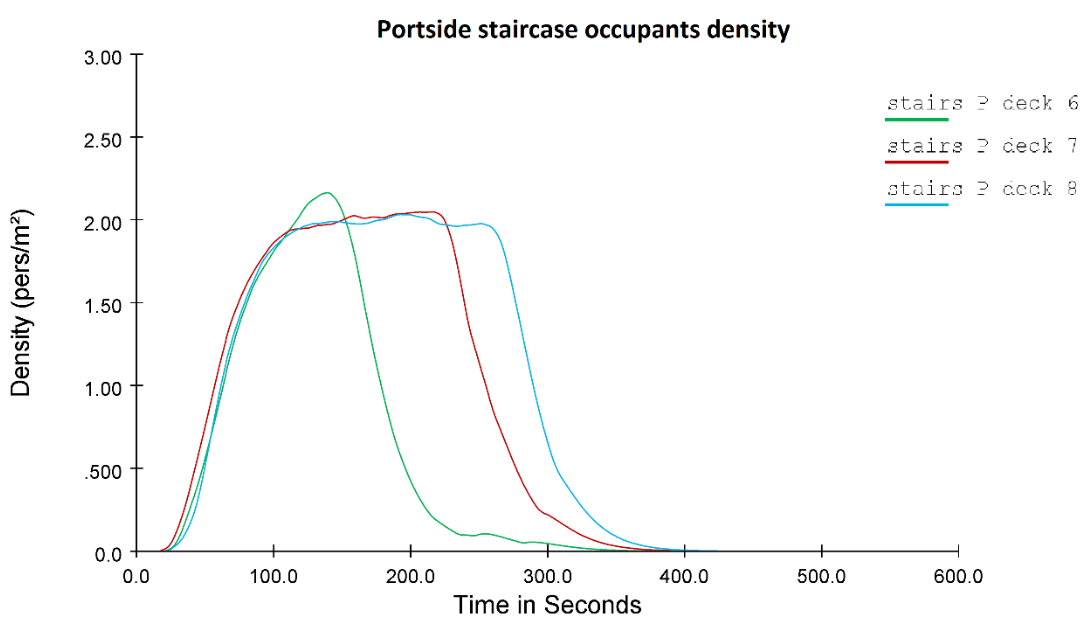


Figure 6.15: Density of occupants at i) starboard & ii) portside staircases & iii) exit way corridors, 50% less exits case

75% less exits (12 out of 16):





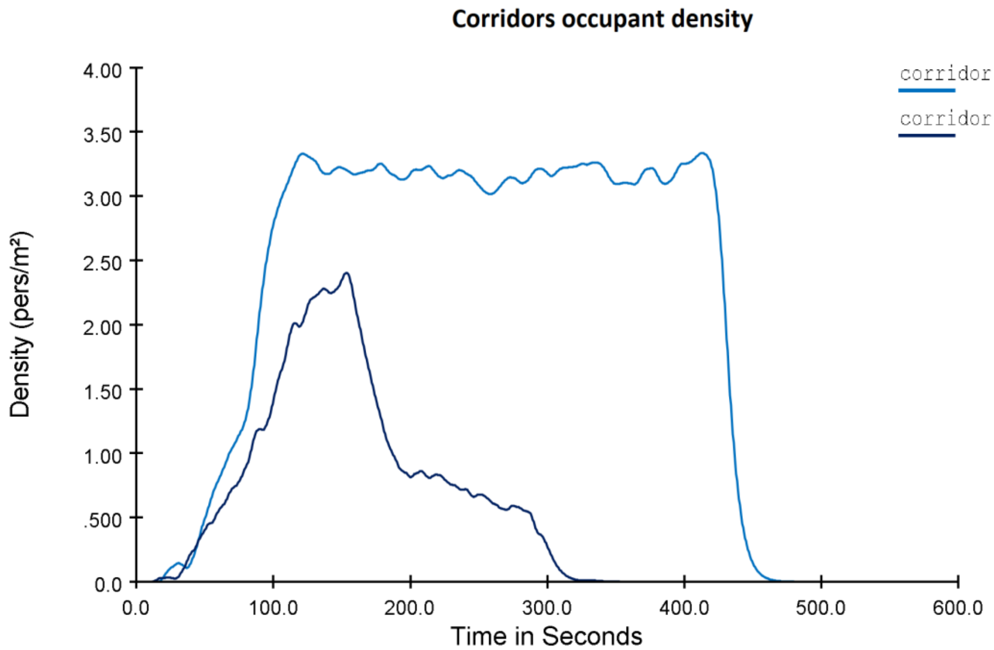


Figure 6.16: Density of occupants at i) starboard & ii) portside staircases & iii) exit way corridors, 75% less exits case

<u>Comments:</u>

As more exits become unavailable, the evacuation time increases. 12.5% less exits cause 5% (+15.1 seconds) increased times compared to the nominal case. Whereas 50% and 75% cause 26% (+74.4 seconds) and 68% (+196.3 seconds), respectively. This dramatic increase is attributed to the uneven disabling of the exits across the decks. If this disabling happened uniformly in each deck e.g. half doors in each deck for the 50% case, the increase would be more gradual and slighter, instead. As a result, the total of occupants of deck 6 and 7 congested in the staircases on their exit ways of decks 8 and 9, as shown in Figure 6.17.

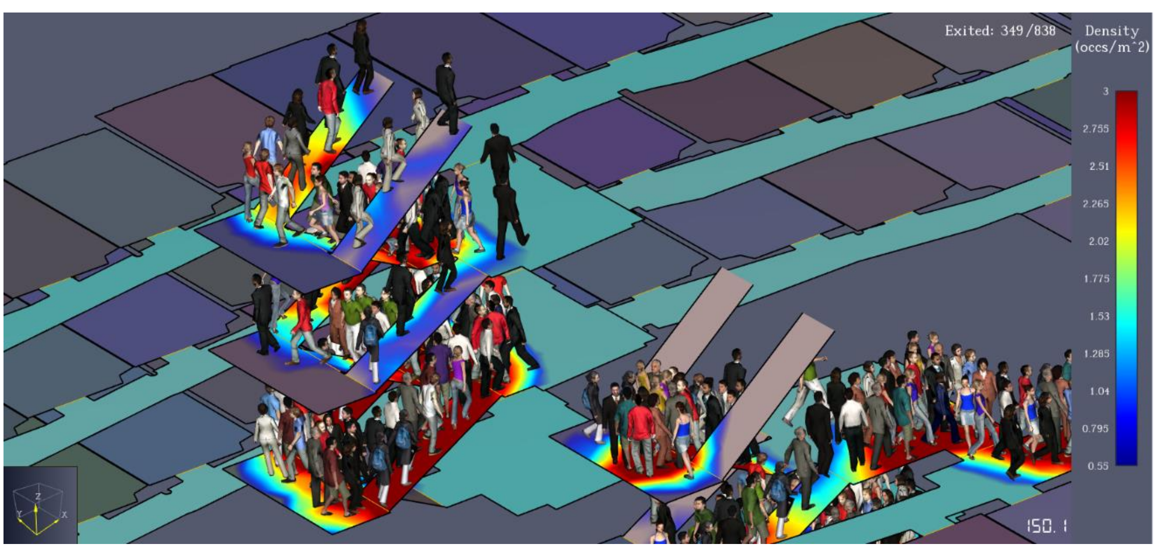


Figure 6.17: Contour plot of less exits doors case with staircases highly congested

The evacuation rate of the occupants is significantly reduced by decreasing more exits, according to the Figure 6.14. Noticeable delay is seen on the average, mainly due to the aforementioned congestion on the stairway in the 2 greater cases. On the 12.5% case, the exit time of 50% of total occupants is 7.7% increased and the average exit time 8.7% to the normal case, according to Table 6.9. This is explained, as several occupants have to alter the exit way path causing 21% increase at the maximum distance travel to the exit way. On the 50% and 75% cases, though, the exit times of 50% of total occupants are doubled (+103%) and even over tripled (+228%) compared to the nominal case. That is also confirmed from the average exit time that is 105% and 192% increased, respectively.

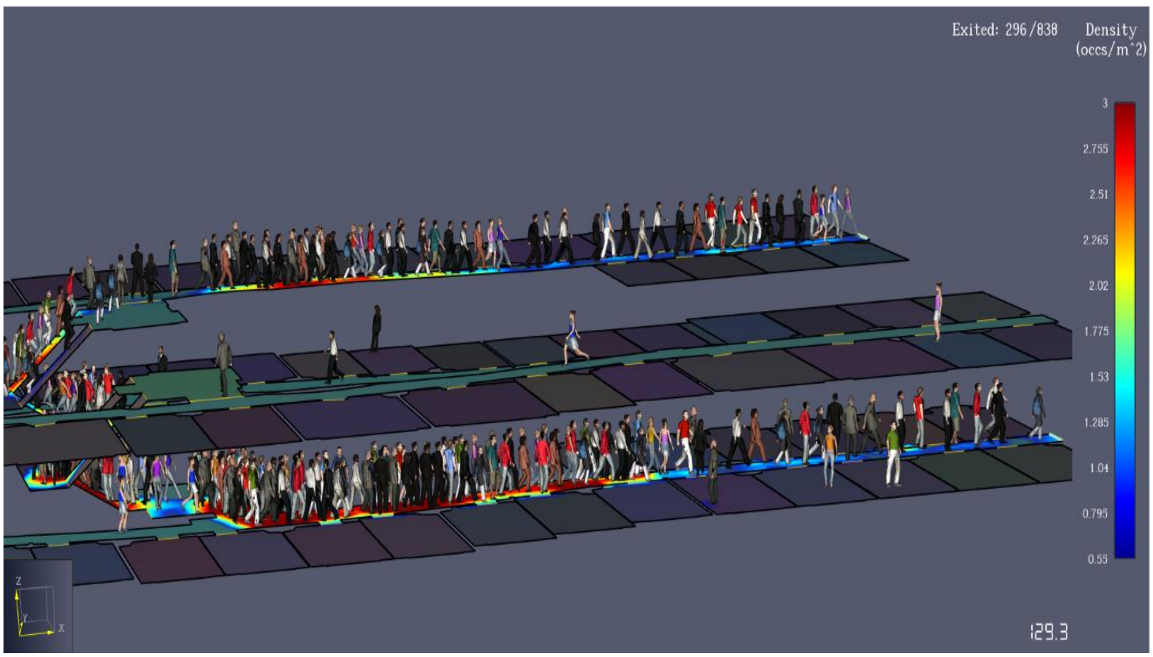


Figure 6.18: Contour plot of less exits doors case with corridors to exit doors 8FS & 9FP congested

As for the congestion, according to Figure 6.15, at 50% less exits case it is obvious that there is significant congestion in the stairway areas, with greater the starboard one, as it is accessible for more occupants than the portside one. Highest density values were 3.1 pers/m^2 and 4.5 pers/m^2 for portside and starboard stairways, respectively. Nevertheless, the corridors to the exit doors of deck 8 found to barely congested as the highest value was 2.96 pers/m^2. As shown in Figure 6.16, on 75% less exits case, same as the previous, the congestion caused in the starboard stairway is greater. Maximum density is 4.8 pers/m^2, whereas maximum density of the portside stairway is 2.8 pers/m^2. Corridor of deck 8 was continuously congested with a maximum density of 3.5 pers/m^2, and deck 9 found to be barely congested with a maximum of 2.7 pers/m^2, as shown in Figure 6.18.

6.5.5 Panic Behavior of Occupants Scenario

Description:

Many people experienced the panic behavior as the evacuation process progressed. The panic contains to a certain extent the behaviors of confusion and anxiety of the individual; when the person is under the influence of panic the following occur:

- 20% increase of their movement speed throughout the total evacuation process (Helbing, & Johansson, 2014).
- when the passenger is in a panic and have to choose a door, the correct choice, dead ends and wrong choices, all have the same probability (Zhang et al., 2013).
- in case a person in panic choose a wrong option, the delay until they understand that there is no available exit is taken as follows: the person will go to the point and after 15-30 sec. will go to the next option (Kady et al., 2009; Kang et al., 2011; Wu et al., 2020).

Based on the above findings, three different subcases are studied, in order to conclude the sensitivity of the evacuation time to the panic:

I. 5% of the total occupants with panic behavior (42 out of 838)
II. 20% of the total occupants with panic behavior (168 out of 838)
III. 40% of the total occupants with panic behavior (336 out of 838)

Setup notes:

At first, occupants who will be in panic will be chosen randomly in the process, using a random number generator. The numbers occurring correspond to each occupant id number (1-838). For validity purposes, five (5) simulations for each subcase will be run, with different panic population each, and the final results will be extracted as an average.

There will be two (2) profiles in each simulation. The normal “Males 30-50 years old” and the “Panic”, which is based on the first one but with 20% increased movement speed, ranging between [1.164 m/s, 1.944 m/s] and also on the following movement options; All attractors allowed is enabled, as well as attractor susceptibility (seeking & waiting) are 100%. So, the profiles in the cases populations are distributed as follows:

I. 5% Panic (42 occupants) – 95% normal (796 occupants)
II. 20% Panic (168 occupants)– 80% normal (670 occupants)
III. 40% Panic (336 occupants)– 60% normal (502 occupants)

Attractors have been put manually at area points (doors, dead ends) that could be considered as wrong choices by occupants with in panic, during the evacuation process, in the whole evacuation area (decks 6,7,8,9). Occupants in panic, that are within the influence radius of an attractor and have direct vision of it (line-of-sight awareness attractors) have a 50% possibility to get attracted by each (because right and wrong choices have now equal probabilities to happen), and if so, they will wait there for an amount of time, before keeping on their exit way. The standby time is a uniform distribution between [15 sec, 30 sec].

Results:

The total evacuation times were 303.5 s, 329.8 s and 336.5 s for subcase 5, 20 and 40%, respectively. Figure 6.19 below presents the total percentage of occupants evacuated as a function of the evacuation time, in comparison to the nominal case, as well.

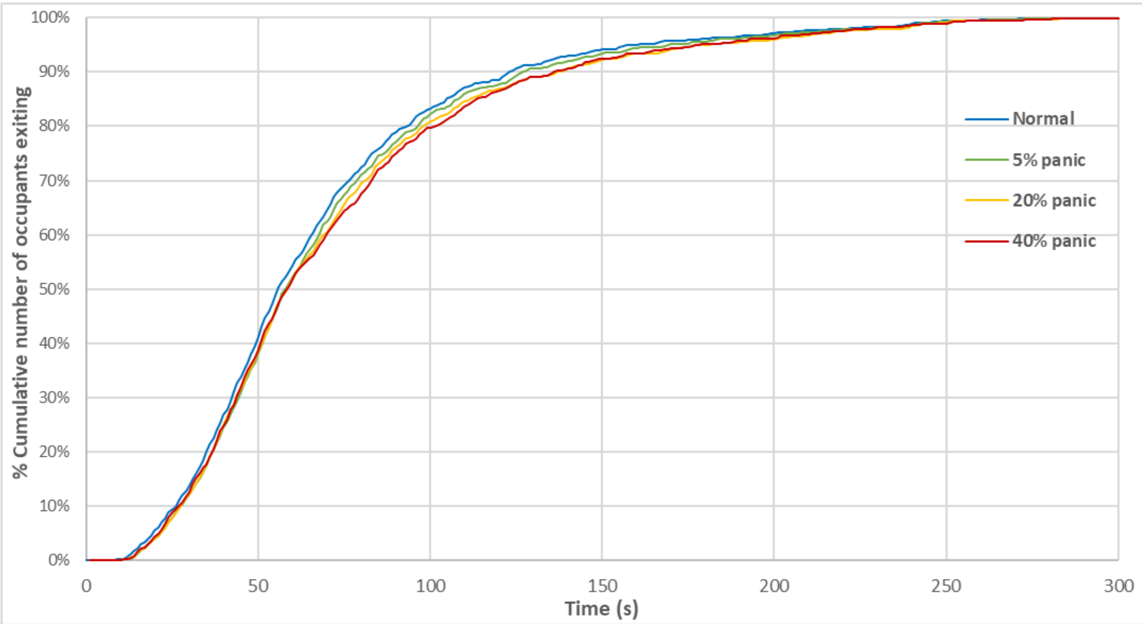


Figure 6.19: Cumulative number of occupants exiting (%), panic behavior cases

The general results of the simulations are presented on the Table 6.11:

Case	**First exiting (s)**	**Last exiting(s)**	**Average exit time (s)**	**Maximum travel distance NORMAL (m)**	**Maximum travel distance PANIC (m)**	**50% occupants exited (s)**	**75% occupants exited (s)**	**90% occupants exited (s)**
5% in panic	6.4	303.5	68.9	101	196.6	56.4	84.7	124.9
INCREASE FROM NORMAL (%)		**5.6%**	**1%**		**152%**	**1.2%**	**1.4%**	**1.6%**
20% in panic	6.2	329.8	70.8	164.6	232.4	56.5	87	133.1
INCREASE FROM NORMAL (%)		**15%**	**3.8%**		**198%**	**2%**	**4.8%**	**8.2%**
40% in panic	6.2	336.5	71.3	78.9	237.2	56.6	87.9	138
INCREASE FROM NORMAL (%)		**17%**	**4.6%**		**204%**	**1.6%**	**18%**	**12%**

Table 6.11: General results, panic behavior cases

Comments:

Increasing number of occupants in panic cause the slight but gradual increase of evacuation time, according to Figure 6.19. 5.6, 15 and 17%, for the three scaling cases respectively, is the actual increase of evacuation times compared to the nominal case. The smoothness in increase of total time as the panic population raises is attributed to two basic factors. On the one hand, the 20% increased speed of people in panic decreases the evacuation time, in principle. On the other hand, this haste is neutralized by their wrong choices, making them waste 15-30 seconds for each one they make. Overall, occupants in panic end up walking long distances upon finding their exit path; 152, 198 and 204% increased distances compared to normal paths for the three cases, respectively, with time consuming standbys that increase the total evacuation time, eventually. Considering the above factors, by doubling or even quadrupling the panic population, the evacuation times do not have dramatic differences but raise incrementally.

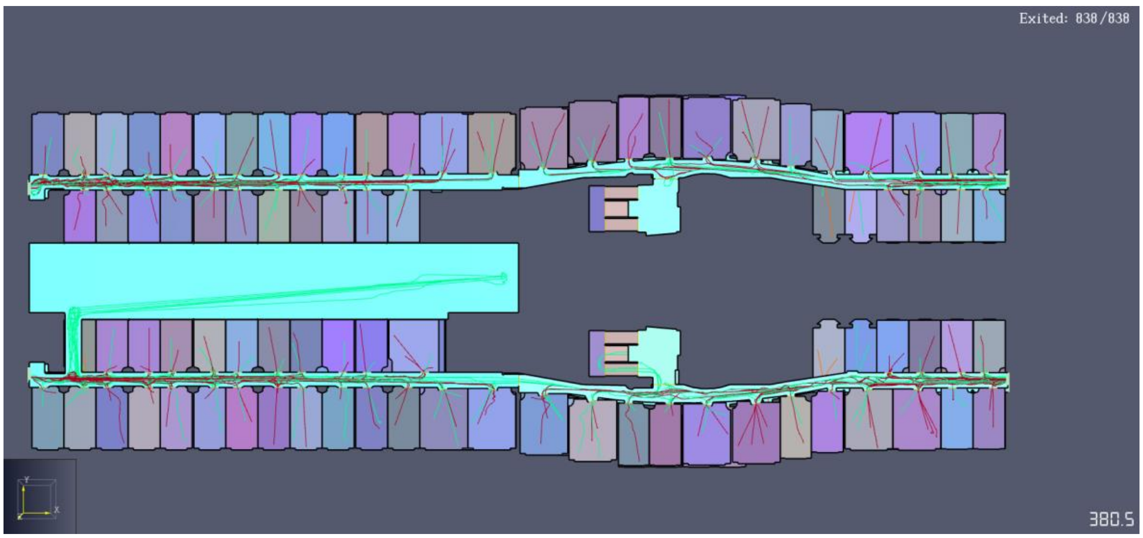


Figure 6.20: Contour plot of 5% panic behavior case with occupants' exit paths (green path-panic)

6.5.6 Combined Scenarios

Description:

After running each scenario individually, it must be examined whether evacuation times of combined scenarios occur by summing up each one individually, or not. Thus, three combined scenarios of the aforementioned were chosen as sample of examination, each of those combined with the case of 50% less available exits:

4. Ship heeling 10-20 degrees
5. Medium visibility reduction
6. 20% of occupants in panic

Setup notes:
The setting up of the simulation goes in each of three cases as before, but with the modification of disabling deck 6 and 7 exit doors. The rest settings remain identical.

Results:

The total evacuation times were 377 s, 599.5 s and 503.9 s for heel 15-20 degrees+50% less exits, medium visibility+50% less exits and 20% panic+50% less exits, respectively. Figure 6.21 below presents the total percentage of occupants evacuated as a function of the evacuation time, in comparison to the nominal case.

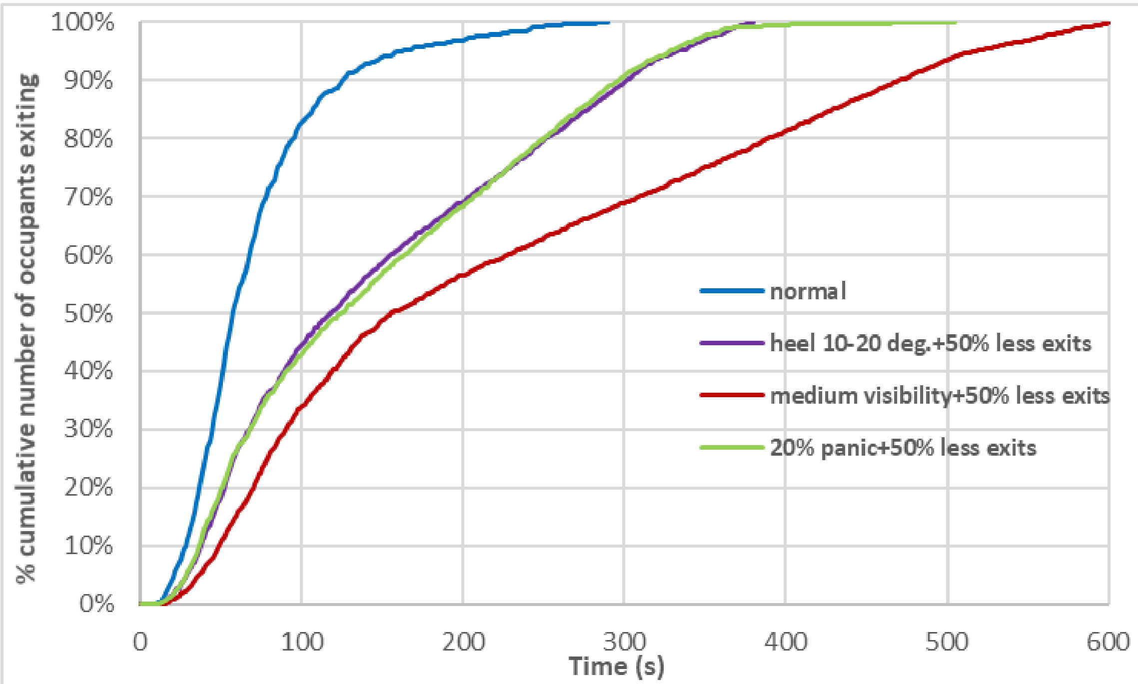


Figure 6.21: Cumulative number of occupants exiting (%), combined cases

The results data of the simulations are presented on the Table 6.13:

		50% LESS EXITS + HEEL 10˚-20˚	50% LESS EXITS + MEDIUM VISIBILITY	50% LESS EXITS + 20% PANIC
COMBINED	**Total evacuation time(s)**	377	599.5	503.9
	% increase from normal	**31%**	**109%**	**75%**
	% summed up increase from normal	**27%** **(26%+1.25%)**	**46%** **(26%+20%)**	**41%** **(26%+15%)**
	50% of occupants exited (s)	116.5	153.8	122.5
	% increase from normal	**109%**	**176%**	**120%**
	% summed up increase from normal	**106%** **(103%+3%)**	**144%** **(103%+41%)**	**104%** **(103%+1.4%)**

	75% of occupants exited (s)	227.4	350	226.7
	% increase from normal	**174%**	**321%**	**173%**
	% summed up increase from normal	**168%** (164%+3.6%)	**197%** (164%+33%)	**169%** (164%+4.8%)
	90% of occupants exited (s)	300	468.5	294.6
	% increase from normal	**144%**	**281%**	**140%**
	% summed up increase from normal	**135%** (134%+0.8%)	**153%** (134%+19%)	**142%** (134%+8.2%)

Table 6.13: Combination scenarios evacuation time & % increase comparisons

- % increase from normal: refers to the combined scenario evacuation time increase from normal.
- % summed up increase from normal: refers to the individual cases' increase from normal, summed up. It occurs a collective increase from normal that is compared to the above actual increase.

Comments:

According to Figure 6.21, the evacuation completion rates comply with the corresponding total evacuation times. Exception to this rule is the 20%panic+50% less exits case. The evacuation completion rate is almost identical to the heel 15-20 degress+50% less exits case, as concluded from the percentile completion of evacuation results, but the total evacuation time is 34% (127 s) slower than latter one. This delay is attributed to the remaining few occupants in panic trying to find the exit path. Furthermore, deriving data from the Table 6.13, it is valid to state that there is no summing up rule of the evacuation times, if we combine two different scenarios. Also, the occurring results from the actual combined cases are sometimes even two times greater than the summed-up ones. This is apparent on case of 50% less exits with medium visibility reduction, giving a sum of 46% increased time to the normal case, whereas the actual combined scenario's evacuation time is eventually 109% increased to the nominal case.

6.5.7 Aggregated Results

Table 6.14 with the total results of all the individual scenarios follows:

	CASES									
	NORMAL	HEEL 10-20 DEG	MEDIUM VISIBILITY 0.3 OD/m	HARSH VISIBILITY 0.5 OD/m	12.5% unavailable exits	50% unavailable exits	75% unavailable exits	5% passengers in panic	20% passengers in panic	40% passengers in panic
First exiting (s)	6.4	6.4	8.1	12.5	6.4	6.4	11.3	6.4	6.2	6.2
Last exiting(s)	287.4	291	345.2	480.4	302.5	361.8	483.7	303.5	329.8	336.5
% Increase from normal		1.25%	20%	67%	5%	26%	68%	5.60%	15%	17%
Average exit time (s)	68.2	69.4	87.2	129.7	74.1	139.9	199.4	68.9	70.8	71.3
% Increase from normal		1.8%	28%	90%	8.7%	105%	192.4%	1%	3.8%	4.6%
Minimum travel distance(m)	3	2.5	2.7	2.8	3	3	3	2.9	3.0	3.2
Maximum travel distance(m)	77.9	77.5	80.7	79.1	94	152	168.1	196.6	232.4	237.2
% Increase from normal		-0.5%	3.6%	1.5%	21%	95%	116%	152%	198%	204%
Time of 50% occupants exited (s)	55.7	57.5	78.4	122.7	60.8	113.2	182.7	56.4	56.5	56.6
% Increase from normal		3%	41%	120%	7.7%	103%	228%	1.2%	1.4%	1.6%
75% occupants exited (s)	83	86	110.4	169.5	94.8	219.5	285.7	84.7	87	87.9
% Increase from normal		3.6%	33%	104%	14%	164%	244%	2%	4.8%	18%
90% occupants exited (s)	123	124	146.2	221	137.5	287.8	390	124.9	133.1	138
% Increase from normal		0.8%	19%	80%	12%	134%	217%	1.5%	8.2%	12%

Table 6.14: Aggregated results of all simulation scenarios

7 Conclusions

In the current thesis a significant part of the analysis process was the preliminary study and especially the verification of the functions & settings of the simulation program to obtain valid results; but also, the study of the relevant parameters to simulate the behavior and profile of passengers in the various scenarios studied. In the ship evacuation model in the pathfinder environment where the scenarios were simulated, some permissible assumptions were made to facilitate the conduct of the study. However, the realism of the model has become sufficient so that the results can be logically characterized in the context of a process of abandoning a cruise ship. These assumptions were taken in such a way that they do not affect the nature of the parameters, the flow of the simulation and the qualitative results of the scenarios examined. But for the temporal and practical facilitation of the student. The assumptions made are:

- The behavior of all occupants in every simulation is “day case”, corresponding to the day case initial delay, as proposed by IMO. This assumption was made to facilitate the processing and comparison of the output results, since the only difference between day and night scenarios is their initial delay times. Something that does not concern, nor does it affect the purpose of this study.

- The cabin areas have their maximum capacity, opposed to the MSC.1/Circ.1533, that in the “day scenario” 100% of passengers is found in public spaces. So, eventually, the IMO based night scenario is considered as the “day case” of our simulations, as it does not affect the actual quality of the extracted results for our sensitivity analysis scope.

- Same as the above, the profile of occupants is selected to be common for all occupants, as “Males 30-50 years old”, randomly. This modification is of significant importance, as it ignores the interaction of other factors in the output results (e.g. speed diversity). Hence, it enables to isolate only the results we need for the thesis scope, without admixtures.

- Passengers are not assigned to exit from specific doors, but it is on their own preference

- Speed of passengers on reduced visibility cases corresponds to non-irritant wood smoke, and the reduction is common for all.

- The reduction speed factors correspond to the middle data of each case range, as an average representative value (e.g. heel angle range, optical density range)

Nevertheless, the occurring results obtained from the model are realistic and scientifically correct given the assumptions made. Specifically:

- The role of fire in the analysis, as a probable cause of affection, affects only the speed of movement and the availability of exits. As a result, neither toxic emissions nor increased heat that can lead to the death of the passengers are introduced, and also there is no possibility of a large-scale fire in the area under study.

- Ship heeling angle has slight impact on the evacuation time, even at great angles (10-20 degrees).

- Reduced visibility due to smoke has severe impact on the evacuation times, as they cause significant decrease of passengers' speed. Increase of time 20-67%, proportional to the harshness of the visibility reduction.

- On the unavailability of exit doors, the gradual scenarios show how the congestion impacts severely on the evacuation time, as well as, the dissimilarity and asymmetry of the out-of-order exit doors across the decks can affect the exiting time. The total increase ranges from 5% to 68%, depending on the above factors, proportionally.

- The behavior of the passengers' panic is a variable that moderately affects the evacuation times of the passengers, since the passengers do move faster than normal but they have abnormal behavior and their movements and choices are characterized as irrational taking wrong choices and even dead ends. It was observed that the exiting time due to the panic variable increases between 5.5-17% in the work model, depending on the percentage of passengers under panic.

Further research and development of such study process evacuation may include the following:

- Participation of various demographic characteristics of the occupants involved in the process, in the various scenarios that have been examined.
- Dynamically switching the number of people who are in panic in the process according to high congested spaces, as crowding may cause nervousness in some passengers.
- Examination of impact of children and their behavior as well as movement impaired passengers on wheelchairs during the evacuation process.
- Integration of fire features such as release of toxic substances, that may affect other variables in the evacuation process apart from those of speed and exit doors unavailability.
- Simulation of the evacuation process of more ship spaces in order to make it fully probabilistic and realistic.
- Complete evacuation analysis of a passenger ship simulating also the E+L “Abandonment time” of passengers in lifeboats.

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Appendix

This appendix includes the results and data outputs for the exit doors of each scenario of the sensitivity analysis that have been examined in Chapter 6.5.

Table 6.4 shows the exit doors results of normal scenario.

	DOORS	FIRST IN(s)	LAST OUT(s)	TOTAL USE (pers)	FLOW AVG(p/s)	MAXIMUM FLOW RATE(p/s)	MAXIMUM SPECIFIC FLOW(p/m/s)
NORMAL	**6 FS**	16	241.3	44	0.2	2	1.82
	6 AP	12.3	249.4	52	0.22	2	1.82
	6 AS	15	287.4	74	0.27	2	1.82
	6 FP	12.1	237	44	0.2	2	1.82
	7 FS	8.7	259.5	44	0.18	2	1.82
	7 AP	13.9	270.2	52	0.2	2	1.82
	7 AS	19.2	226.7	76	0.37	2	1.82
	7 FP	11.7	237.6	44	0.19	2	1.82
	8 FS	15.5	280.3	42	0.16	2	1.82
	8 AP	11.3	148.5	52	0.38	2	1.82
	8 AS	19.2	240.3	76	0.34	2	1.82
	8 FP	13	208.9	42	0.21	2	1.82
	9 FS	6.4	199	44	0.23	2	1.82
	9 AP	15	239.2	54	0.24	2	1.82
	9 AS	15.3	239.7	54	0.24	2	1.82
	9 FP	17.6	215	44	0.22	2	1.82

Table 6.4: Exit doors results, normal case

Table 6.6 shows the exit doors results of ship heeling scenario.

	DOORS	FIRST IN(s)	LAST OUT(s)	TOTAL USE (pers)	FLOW AVG(p/s)	MAXIMUM FLOW RATE(p/s)	MAXIMUM SPECIFIC FLOW(p/m/s)
HEEL 10˚ -20˚	**6 FS**	16.4	242.8	44	0.19	1	0.91
	6 AP	12.6	251	52	0.22	2	1.82
	6 AS	15.3	291	74	0.27	2	1.82
	6 FP	12.5	237.9	44	0.2	1	0.91

	7 FS	8.8	260.2	44	0.18	2	1.82
	7 AP	14.3	271	52	0.2	2	1.82
	7 AS	19.7	228.4	76	0.36	2	1.82
	7 FP	11.9	238.1	44	0.19	1	0.91
	8 FS	15.6	280.9	42	0.16	2	1.82
	8 AP	11.7	150	52	0.38	2	1.82
	8 AS	19.5	240.6	76	0.34	2	1.82
	8 FP	13.4	209.8	42	0.21	2	1.82
	9 FS	6.4	199.2	44	0.23	2	1.82
	9 AP	15.3	240.8	54	0.24	2	1.82
	9 AS	15.6	241.1	54	0.24	2	1.82
	9 FP	18	216.4	44	0.22	2	1.82

Table 6.6: Exit doors results, ship heeling

Table 6.8 shows the exit doors results of reduced visibility scenarios.

	DOORS	**FIRST IN(s)**	**LAST OUT(s)**	**TOTAL USE (pers)**	**FLOW AVG(p/s)**	**MAXIMUM FLOW RATE(p/s)**	**MAXIMUM SPECIFIC FLOW(p/m/s)**
MEDIUM VISIBILITY REDUCTION [0.3 OD/m^{-1}]	**6 FS**	19.1	265.4	44	0.18	1	0.91
	6 AP	16.5	271.9	52	0.2	2	1.82
	6 AS	18.5	345.2	74	0.23	2	1.82
	6 FP	16.5	252.1	44	0.19	1	0.91
	7 FS	17.5	289	42	0.15	2	1.82
	7 AP	16	174.1	52	0.33	1	0.91
	7 AS	23	247.7	76	0.34	2	1.82
	7 FP	16.9	221.8	42	0.2	1	0.91
	8 FS	15.6	280.9	42	0.16	1	0.91
	8 AP	11.7	150	52	0.38	1	0.91
	8 AS	19.5	240.6	76	0.34	1	0.91
	8 FP	13.4	209.8	42	0.21	1	0.91
	9 FS	8.1	202.7	44	0.23	1	0.91
	9 AP	20.4	265.5	54	0.22	1	0.91
	9 AS	22	262.1	54	0.22	1	0.91
	9 FP	24.5	236.9	44	0.21	1	0.91

	DOORS	FIRST IN(s)	LAST OUT(s)	TOTAL USE (pers)	FLOW AVG(p/s)	MAXIMUM FLOW RATE(p/s)	MAXIMUM SPECIFIC FLOW(p/m/s)
HARSH VISIBILITY REDUCTION [0.5 OD/m^{-1}]	**6 FS**	25	321.7	44	0.15	2	1.82
	6 AP	23.8	327.2	52	0.17	1	0.91
	6 AS	25	480.4	74	0.16	2	1.82
	6 FP	26.9	287.6	44	0.17	2	1.82
	7 FS	20.8	294.5	44	0.16	1	0.91
	7 AP	25.5	308.5	52	0.18	1	0.91
	7 AS	39.5	317.1	76	0.27	1	0.91
	7 FP	22.3	276.5	44	0.17	1	0.91
	8 FS	22.1	309.5	42	0.15	1	0.91
	8 AP	26.7	233.3	52	0.25	1	0.91
	8 AS	29	282.6	76	0.3	1	0.91
	8 FP	26	252.2	42	0.19	1	0.91
	9 FS	12.5	250.1	44	0.19	1	0.91
	9 AP	25.9	326.6	54	0.18	1	0.91
	9 AS	37.7	314.5	54	0.2	1	0.91
	9 FP	38.9	289	44	0.18	1	0.91

Table 6.8: Exit doors results, reduced visibility cases

Table 6.10 shows the exit doors results of limited availability of exit doors scenarios.

	DOORS	FIRST IN(s)	LAST OUT(s)	TOTAL USE (pers)	FLOW AVG(p/s)	MAXIMUM FLOW RATE(p/s)	MAXIMUM SPECIFIC FLOW(p/m/s)
2 out of 16 exits (12.5%)	**6 FS**	16	302.5	118	0.41	2	1.82
	6 AP	12.3	249.4	58	0.24	2	1.82
	7 FS	8.7	259.5	44	0.18	2	1.82
	7 AP	13.9	270.2	52	0.2	2	1.82
	7 AS	19.2	226.7	76	0.37	2	1.82
	7 FP	11.7	274.6	82	0.31	2	1.82
	8 FS	15.5	280.3	42	0.16	2	1.82
	8 AP	11.3	148.5	52	0.38	2	1.82
	8 AS	19.2	240.3	76	0.34	2	1.82
	8 FP	13	208.9	42	0.21	2	1.82

	9 FS	6.4	199	44	0.23	2	1.82
	9 AP	15	239.2	54	0.24	2	1.82
	9 AS	15.3	239.7	54	0.24	2	1.82
	9 FP	17.6	215	44	0.22	2	1.82

8 out of 16 exits (50%)	**DOORS**	**FIRST IN(S)**	**LAST OUT(S)**	**TOTAL USE (PERS)**	**FLOW AVG(P/S)**	**MAXIMUM FLOW RATE(p/s)**	**MAXIMUM SPECIFIC FLOW(p/m/s)**
	8 FS	15.5	361.8	279	0.81	2	1.82
	8 AP	11.3	148.5	52	0.38	2	1.82
	8 AS	19.2	320.9	77	0.26	2	1.82
	8 FP	13	333.6	234	0.73	2	1.82
	9 FS	6.4	199	44	0.23	2	1.82
	9 AP	15	239.2	54	0.24	2	1.82
	9 AS	15.3	239.7	54	0.24	2	1.82
	9 FP	17.6	215	44	0.22	2	1.82

12 out of 16 exits (75%)	**DOORS**	**FIRST IN(S)**	**LAST OUT(S)**	**TOTAL USE (PERS)**	**FLOW AVG(P/S)**	**MAXIMUM FLOW RATE(p/s)**	**MAXIMUM SPECIFIC FLOW(p/m/s)**
	8 FS	15.5	483.7	396	0.85	2	1.82
	8 AP	11.3	215	77	0.38	2	1.82
	9 AS	15.3	239.7	58	0.26	2	1.82
	9 FP	17.6	347.4	307	0.93	2	1.82

Table 6.10: Exit doors results, limited availability of exit doors cases

Table 6.12 shows the exit doors results of panic behavior scenarios.

5% in PANIC	**DOORS**	**FIRST IN(s)**	**LAST OUT(s)**	**TOTAL USE (pers)**	**FLOW AVG(p/s)**	**MAXIMUM FLOW RATE(p/s)**	**MAXIMUM SPECIFIC FLOW(p/m/s)**
	6 FS	15.5	241.3	44	0.20	2	1.82
	6 AP	12.3	249.4	52	0.22	1	0.91
	6 AS	15.0	303.5	74	0.26	2	1.82
	6 FP	11.9	237.0	44	0.20	2	1.82
	7 FS	8.7	259.5	44	0.18	2	1.82
	7 AP	13.9	269.7	52	0.20	2	1.82
	7 AS	19.0	230.0	76	0.37	2	1.82
	7 FP	11.5	237.6	44	0.19	2	1.82

	8 FS	15.5	280.3	42	0.16	2	1.82
	8 AP	11.1	149.2	52	0.38	2	1.82
	8 AS	19.2	240.3	76	0.34	2	1.82
	8 FP	13.0	208.9	42	0.21	2	1.82
	9 FS	6.4	199.0	44	0.23	2	1.82
	9 AP	15.0	239.2	54	0.24	2	1.82
	9 AS	15.3	242.5	53	0.23	2	1.82
	9 FP	17.6	214.0	44	0.22	2	1.82

	DOORS	**FIRST IN(s)**	**LAST OUT(s)**	**TOTAL USE (pers)**	**FLOW AVG(p/s)**	**MAXIMUM FLOW RATE(p/s)**	**MAXIMUM SPECIFIC FLOW(p/m/s)**
20% in PANIC	**6 FS**	15.5	246.1	44	0.19	2	1.82
	6 AP	12.0	249.3	52	0.22	2	1.82
	6 AS	14.7	329.8	76	0.25	2	1.82
	6 FP	11.9	237.0	44	0.20	2	1.82
	7 FS	8.6	258.6	44	0.18	2	1.82
	7 AP	13.3	269.7	52	0.20	2	1.82
	7 AS	18.1	276.9	77	0.31	2	1.82
	7 FP	11.3	237.2	44	0.19	2	1.82
	8 FS	15.5	280.3	42	0.16	2	1.82
	8 AP	11.1	151.0	52	0.37	2	1.82
	8 AS	19.2	244.3	77	0.34	2	1.82
	8 FP	13.0	208.9	42	0.21	2	1.82
	9 FS	6.2	198.8	44	0.23	2	1.82
	9 AP	14.5	239.2	54	0.24	2	1.82
	9 AS	16.5	235.0	50	0.24	2	1.82
	9 FP	17.0	214.0	44	0.22	2	1.82

	DOORS	**FIRST IN(s)**	**LAST OUT(s)**	**TOTAL USE (pers)**	**FLOW AVG(p/s)**	**MAXIMUM FLOW RATE(p/s)**	**MAXIMUM SPECIFIC FLOW(p/m/s)**
40% in PANIC	**6 FS**	15.3	251.0	44	0.19	2	1.82
	6 AP	11.5	248.8	52	0.22	2	1.82
	6 AS	14.4	336.5	76	0.25	2	1.82
	6 FP	11.8	236.3	44	0.20	1	0.91
	7 FS	8.4	258.6	44	0.18	2	1.82
	7 AP	13.3	269.2	52	0.20	2	1.82
	7 AS	18.8	290.3	78	0.31	2	1.82
	7 FP	11.3	236.4	44	0.20	2	1.82

	8 FS	10.8	149.9	52	0.37	2	1.82
	8 AP	11.1	151.0	52	0.37	2	1.82
	8 AS	18.7	259.7	76	0.32	2	1.82
	8 FP	12.5	207.2	42	0.22	2	1.82
	9 FS	6.2	198.8	44	0.23	2	1.82
	9 AP	14.7	233.5	54	0.25	2	1.82
	9 AS	18.3	213.8	50	0.26	2	1.82
	9 FP	16.7	219.8	44	0.22	2	1.82

Table 6.12: Exit doors results, panic behavior cases